

AN ELECTROMYOGRAPHIC EXAMINATION  
OF LIP ASYMMETRY DURING  
SPEECH AND NON-SPEECH ORAL MOVEMENTS  
IN ADULTS WHO STUTTER

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## Abstract

Past research investigating stuttering has cited atypical cerebral lateralization in adults who stutter (AWS) during speech production. The purpose of this study was to measure cerebral activation in AWS as indicated by lip asymmetry. The study included five AWS (mean age = 26 years of age) and five adults who do not stutter (AWNS) (mean age = 25 years of age). The tasks included single-word productions, single-sentence readings and lip pursings. The peak electromyographic (EMG) amplitude was determined for the left upper, right upper, left lower and right lower lip quadrants around the mouth. Overall, EMG amplitudes were higher for the lower lip than the upper lip. Based on examination of peak EMG amplitude, significant differences were found between speaker groups. For both speech and non-speech tasks, the highest EMG amplitude for the AWS and AWNS groups were on the left lower and right lower sides of the mouth, respectively. The AWNS group showed strong correlations in EMG activity across the four lip sites ( $r > 0.97$ ), indicating an overall synchronous lip activity during speech and non-speech tasks. In contrast, the AWS group showed a strong correlation ( $r = 0.97$ ) only for the left upper and left lower lips while the other lip pairings were not strongly correlated ( $r < 0.738$ ) indicating otherwise reduced synchronous lip activity. While the small sample size suggests caution, clear differences in the pattern of lip EMG activity demonstrated in the present study provides evidence of differences between AWS and AWNS in the cerebral activation governing lip movement. The greater left lip activity observed in AWS was indicative of greater right hemisphere cerebral activation while increased right lip activity was indicative of greater left hemisphere participation in AWNS. The results of the present study provided support for the hypotheses of reversed lateralization for speech and non-speech processing and reduced coordination of speech musculature in AWS.

## **Introduction**

Stuttering is a speech disorder that occurs in about one percent of the population (Brown et al., 2005). Similar to other speech and language disorders, stuttering affects three to four times as many males than females (Bloodstein, 1987; Buchél & Sommer, 2004). The onset of stuttering usually occurs around three years of age, during periods of rapid cognitive, linguistic and motor development (Yairi & Ambrose, 2004; Weber-Fox, 2001). About 80% of children recover naturally but recovery rates are higher in girls than boys and drop with increasing age (Howell, 2007; Packman et al., 2007). About 50% of stutterers report a family history of stuttering (de Felicio et al., 2007), which has supported links to a genetic component to stuttering (Kent, 1983). In addition, motor coordination, linguistic constraints, emotion, and structural and functional anomalies, specifically in relation to brain organization have been cited as critical factors in stuttering (Bernstein-Ratner, 1997; Bloodstein, 2006; Ezrati-Vinacour & Levin, 2004; Ingham et al., 2000; Jancke et al., 2004; Ludlow & Loucks, 2003; Yairi et al., 1996).

### **Theories of Stuttering**

Despite intensive research, the exact cause of stuttering has remained elusive. Stuttering is a “complex, multidimensional problem that has defied a variety of simple, unidimensional explanations” (Conture, 1990). Numerous theories have been proposed for the disorder and, as yet, there is no unified theory that accounts for the various aspects of the disorder. Some of the more popular theories that address either the cause of stuttering or the moment of stuttering are presented below.

The Anticipatory-Struggle Hypothesis (Bloodstein, 1987) describes stuttering as a consequence of a child’s negative experiences in talking which is based on a belief that speech is difficult. These negative experiences could result in a number of ways, including

a child's hesitation during speech, the parents' extremely high standards, or communicative pressures. Early disfluency (or Primary Stuttering) is a transient phenomenon if a child is not made aware that his speech is different. Consequently, if a child is alerted to his speech difference, later disfluency (or Secondary Stuttering) will ensue. In Secondary Stuttering, anticipation, fear and avoidance are part of the stuttering phenomenon. Primary and Secondary Stuttering are driven by extrinsic factors such as the perceptions of others toward disfluencies.

A variant of the Anticipatory-Struggle Hypothesis is the Diagnosogenic Theory (Johnson et al., 1959). This classic theory claims stuttering has its roots in the perceptions of others, or the "ear" of the listener. Johnson (1944) reported that the speech of children who stutter (CWS) and children who do not stutter (CWNS) was practically indistinguishable. Johnson concluded that in almost every case of stuttering, the child was misdiagnosed by his parents, or other untrained judges. Similar to the Diagnosogenic Theory, the Demands and Capacities Model of stuttering suggests that extrinsic factors (i.e., demands) such as parental expectations or sibling competition contribute to stuttering (Johnson et al., 1959; Starkweather, 1987; Starkweather & Givens-Ackerman, 1997). Additionally, intrinsic factors (i.e., capacities) are also implicated. The capacities are traits, either innate or acquired which relate directly to the execution of speech production (Starkweather & Givens-Ackerman, 1997). Stuttering results when "a child's capacity for fluency is not equal to speech performance demands" (Guitar, 2006).

The Covert Repair Hypothesis (Postma & Kolk, 1993) suggests that stuttering is due to intrinsic factors. This theory regards disfluency as a product of self-monitoring during linguistic processing and does not make a distinction between normal disfluencies and stuttering. During the formulation of speech, the speaker realizes a linguistic error is about to be committed and attempts to correct the mistake prior to articulation. A

successful repair will result in fluent speech. However, a failed attempt at correction will result in disfluency. Failed attempts occur when the speaker tries to produce speech during the process of a covert speech repair, which subsequently leads to muscle tension and disfluency (Guitar, 2006).

The Psycholinguistic Model of stuttering (Wingate, 1988) views the linguistic process of speech generation/production as a vital element in stuttering. Similar to the Covert Repair Hypothesis (Postma & Kolk, 1993), Wingate's theory suggests that a moment of stuttering occurs because an individual is unable to move forward with his speech due to a linguistic error. Wingate points to faulty phonological encoding as the culprit. The pre-articulatory process specifically, the mistiming of syllable onsets and syllable rhyme retrievals causes speech arrest and failure to move past the syllable onset (Bernstein-Ratner, 1997).

Perkins et al. (1991) proposed the Theory of Neuropsycholinguistic Function to describe stuttering. The theory credits two elements to the production of a stutter: time pressure and speech disruption. The interaction of time pressure and speech disruption results in stuttering which is experienced by the speaker as a loss of control. Speech disruptions occur when the linguistic and paralinguistic components are not in synchrony. The paralinguistic components or socio-emotional process is governed by the right hemisphere, while the linguistic aspects, such as language structure and content, are left hemisphere based (Guitar, 2006). This notion of stuttering associated with anomalous cerebral laterality has been explored since the 1920's.

### **Atypical Cerebral Architecture and Composition related to Stuttering**

Although atypical cerebral laterality has been proposed since the 1920's, it was not until the advent of neuroimaging techniques that these speculations could be substantiated.

Neuroimaging studies have consistently reported a prominent “rightward shift” or lack of asymmetry in the brain of AWS (Foundas et al., 2003; Jancke et al., 2004). For example, Foundas et al. (2003) found atypical symmetry in the lobar architecture, whereby AWS showed right hemisphere temporal-parietal-occipital lobes that were larger or equal in volume to their left hemisphere homologues. In AWNS, the temporal-parietal-occipital regions typically display larger left than right hemisphere volumes. Further, the left prefrontal region in AWS was larger, a reversal of that seen in AWNS (Foundas et al., 2003). In addition, the planum temporale (part of Wernicke’s area) and Heschl’s gyrus (the primary auditory cortex) located within the superior temporal gyrus were reported to be larger in the right hemisphere and more symmetrical in AWS when compared to AWNS (Foundas et al., 2001, 2003; Jancke et al., 2004; Strub et al., 1987). In right-handed AWNS, the leftward asymmetry of the planum temporale, which is involved in phonological encoding, is considered to be a marker of the left hemisphere specialization for language (Beal et al., 2007; Binder et al., 1996; Dorsaint-Pierre et al., 2006; Foundas et al., 1994; Hervé et al., 2006). Thus, the “rightward” asymmetry of the planum temporale in AWS may be an indication of reversed lateralization for language (Strub et al., 1987).

Discrepancies have also been detected in regard to cerebral composition. AWS feature larger volume of white matter in the right hemisphere while AWNS displayed larger volume in the left (Hervé et al., 2006; Jancke et al., 2004). In AWS, increased white matter was reported in the superior temporal gyrus, inferior frontal gyrus and middle frontal gyrus, all of which are involved in auditory and speech processing (Beal et al., 2007; Jancke et al., 2004). Two structures located within the superior temporal gyrus of the right hemisphere, specifically the planum temporale and Heschl’s gyrus, also displayed greater white matter density in AWS than AWNS (Jancke et al., 2004). Differences in white matter composition may be a crucial component in hemispheric lateralization (Hervé

et al., 2006). In addition, the white matter fiber tracts in the left Rolandic operculum of AWS appear to be less dense compared to AWNS (Sommer et al., 2002). CWS display a similar trend of reduced white matter integrity in the left Rolandic operculum (Chang et al. 2008). White matter fibers link the sensory, planning and motor regions of the brain, and are made up mainly of myelinated axons which increase the conduction speed of action potentials (Robinson, 1998). Interestingly, Watkins et al. (2008) documented reduced functional activation in regions with lower white matter integrity specifically, the right premotor cortex and left ventral premotor cortex during sentence reading and auditory feedback in AWS. The increased processing efficiency as a result of greater white matter density in the right hemisphere coupled with reduced white matter integrity of the left Rolandic operculum in AWS may favor language lateralization to the right hemisphere.

Investigations of gray matter density in AWS have been equivocal. Jancke et al. (2004) reported no significant difference in the volume of gray matter between AWS and AWNS. In contrast, Beal et al. (2007) reported an increase of gray matter in AWS in the right and left superior temporal gyrus, left middle temporal gyrus and left inferior frontal gyrus (including the *pars opercularis*). Similarly, CWS showed increased volume of gray matter in the left and right superior temporal gyrus in comparison to CWNS (Chang et al., 2008). Further, among these regions, the right superior temporal gyrus encompassing Heschl's gyrus featured the greatest increase in gray matter in AWS (Beal et al., 2007; Kasai et al., 2003). In AWNS, the left *pars opercularis*<sup>1</sup> and superior temporal gyrus encompassing Heschl's gyrus demonstrate larger volume of gray matter than the right

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<sup>1</sup> In a study of intractable epilepsy, the density of gray matter in the *pars opercularis* was suggested to be a better indicator of language lateralization than the asymmetry of the planum temporale (Dorsaint-Pierre et al., 2006). In individuals who were right hemisphere dominant for language, the gray matter density was consistently greater in the right than left *pars opercularis*. This pattern was not reliably displayed by the planum temporale. The morphological asymmetry of the *pars opercularis* was postulated to reflect use-dependent reorganization.

(Hervé et al., 2006). The bilateral increase of gray matter in the superior temporal gyrus of AWS and children with persistent stuttering which was not observed in AWNS or children who recovered from stuttering may be suggestive of alterations in the cerebral anatomy as a consequence of persistent stuttering (Chang et al., 2008). Additionally, the bilateral increase of gray matter in AWS may be suggestive of participation from both hemispheres for language processing which supports the hypothesis of lack of dominance.

AWS also presented atypical gyrification. Foundas et al. (2001) reported three aberrations related to gyral patterns. This included the presence of an extra gyrus along the superior bank of the sylvian fossa and the frontal operculum. Secondly, AWS presented greater variability in gyral patterns which included arrangements that were confined solely to AWS. For example, a unique variation of the gyral pattern included the occurrence of a second diagonal sulcus resulting in an extra gyrus within the *pars opercularis*. Overall, there was a higher occurrence of atypical gyrification within the AWS group. AWS individuals featured an average of four anomalous configurations which was higher than AWNS individuals who averaged a single atypical configuration. These structural anomalies associated architecture and composition of the cerebrum may be an indicator or predictor of atypical hemispheric dominance and function.

### **Stuttering and Cerebral Activation**

One of the earliest studies investigating cerebral laterality<sup>2</sup> and stuttering was performed by Orton and Travis in 1927 (Bloodstein, 1987). Using electroencephalographic (EEG) techniques, they measured electrical activity of adults who stutter (AWS) and adults

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<sup>2</sup> The phenomenon of laterality can be categorized into functional, anatomical or behavioral events and is not a uniquely human occurrence. Tortoises have a right-handed disposition when righting themselves (Stancher et al., 2006). Even octopi have lateralized usage of the arms and eyes (Bryne et al., 2006). Additionally, zebrafish are more likely to turn right when startled by predators (Watkins et al., 2004). In right-handed human mothers, there is a tendency to hold babies in their left arms (Harris et al., 2000). There is also a preference to turn heads to the right when kissing (Güntürkün, 2003).



who do not stutter (AWNS). The results were compelling, indicating that AWS did not show left hemisphere dominance during speech. This observation was interpreted as a lack of hemispheric dominance in AWS (Travis, 1978) and would later be known as the Theory of Cerebral Dominance. Although the basis of this theory was not substantiated, its idea was paramount to later investigations into the neural basis of stuttering. Subsequent investigations have suggested that lateralization of hemispheric processing may be task dependent. For example, in AWS oral reading generated greater right hemisphere activation when compared to silent reading (De Nil et al., 2000). In general, anomalous patterns of activation have been observed in AWS including (1) over-activation of the cortical and subcortical areas related to motor processing, (2) reduced activation in the regions associated with auditory processing and (3) atypical lateralization (Brown et al., 2005). These anomalous patterns of activation have been observed during disfluent and fluent speech in AWS. Additionally, several studies have documented alterations in cerebral activation following fluency treatment and evidence of right hemisphere compensation in AWS (De Nil et al., 2003; Giraud et al., 2008; Neumann et al., 2005).

### *Disfluent Speech Production*

Anomalous cerebral activations and deactivations have been documented during disfluent speech production in AWS (Fox et al., 1996; Ingham 2004). During moments of stuttering, the motor system was over-activated with prominent right hemisphere lateralization of the primary and extraprimaries cortices (Fox et al., 1996). In the primary motor cortex, the intensity of activation was similar in both groups but right lateralized in AWS and left lateralized in AWNS (Fox et al., 1996). Interestingly, the right superior lateral premotor cortex which documented greater activation during moments of stuttering was only weakly activated during imagined stuttering (Ingham et al., 2000). In addition,

tasks that were defined as disfluency-inducing such as solo reading (as opposed to chorus reading which was regarded as fluency-inducing) activated the left and right supplementary motor area in both groups but with greater intensity in AWS (Fox et al., 1996; Ingham et al., 2000). Greater activity in the medial and dorsolateral prefrontal, and anterior cingulate cortices were also observed during moments of stuttering (Braun et al., 1997). These regions are associated with speech and motor planning (Awh & Gehring, 1999; Turner et al., 2006).

In addition, during disfluent speech production, AWS activated regions that were not activated in AWNS including the left claustrum, left lateral thalamus and left globus pallidus, and the left and right insula (Fox et al., 1996; Ingham et al., 2000, 2004). These regions were not activated during fluent speech in AWS. The globus pallidus is a major component of the basal ganglia and is involved in motor control (Murdoch, 2004). Further, deactivation of the inferior frontal gyrus, an area associated with articulatory movement, was observed during stuttering (Ingham et al., 2004).

During disfluent speech production in AWS, regions for processing sensory information documented reduced levels of activity (Braun et al., 1997). In addition, regions associated with self-monitoring, comprehension and fluency including the left inferior frontal and primary auditory cortices were activated in AWNS but not in AWS during disfluent speech (Braun et al., 1997). Stuttering was negatively correlated with greater activity in the primary auditory and auditory association cortices (Braun et al., 1997; Ingham et al., 2004). Additionally, bilateral activity of the cerebellum became strongly left lateralized during moments of stuttering (Fox et al., 2000; Ingham et al., 2004). Cerebellar activation was also more widespread in AWS than in AWNS (Fox et al., 1996; Braun et al., 1997). The cerebellum has been implicated in cognitive processing and is responsible for timing and coordination of sensorimotor actions (De Nil et al., 2001; Kent, 2004a).

Investigations of disfluent speech production have also focused on children. In a study using EEG technique, when asked to provide a narrative after listening to happy, angry and neutral background conversation, both CWS and CWNS displayed increased speech disfluencies with angry background conversation but CWS were observed to be more emotionally reactive and less effective at regulating their emotions than CWNS (Arnold et al., 2006). CWS were observed to display greater left frontal activity during angry background conversation and greater right parietal activation during happy background conversation compared to CWNS. Although the study was limited to children, it provides insight into emotion and speech production in individuals who stutter.

The results of these investigations positively correlate disfluent speech production with the over-activation of the right cerebral regions associated with speech and motor planning, and the left cerebellum in AWS (Fox et al., 2000). These studies are also suggestive of reduced capacity for auditory monitoring in AWS and further reinforce the hypothesis that right hemisphere participation results in the production of disfluent speech (Ingham et al., 2004; Moore & Lang, 1977).

### *Fluent Speech Production*

Even in the absence of stuttered or overt speech production, differences in cerebral activation have been documented between AWS and AWNS (Biermann-Ruben et al., 2005; Cuadrado & Weber-Fox, 2003). Two different investigations employing the hemispheric alpha-asymmetry technique recorded greater activation in the right hemisphere of AWS even in the absence of stuttering. In the first investigation, Moore and Lang (1977) documented greater left hemisphere activation ( $n=8$ ) or equal bilateral activation ( $n=1$ ) in AWNS during oral reading. In the AWS group, the trend was reversed with eight individuals displaying greater right hemisphere activation and surprisingly, two

individuals displayed greater left hemisphere activation. Wells and Moore (1990) investigated sentence repetition and also documented greater activation of right hemisphere in AWS. Wells and Moore suggest that AWS “might better be characterized as neglecting the left hemisphere, than over-utilizing the right”. These results support the notion of reversed laterality associated with linguistic processing in AWS.

Similarly, PET studies have reported right hemisphere activation in AWS. Braun et al. (1997) reported bilateral activation of the medial and dorsolateral prefrontal cortices, superior anterior cingulate cortex and caudal orbital cortices in AWS. These regions were left hemisphere activated in AWNS. The left middle temporal and inferior angular gyri, and left lateral occipital cortices were activated in AWNS but not in AWS. Additionally, activation of the right caudate nucleus and right inferior anterior cingulate cortex was unique to the AWS group. The caudate nucleus (which is part of the basal ganglia) and anterior cingulate cortex are associated with planning and execution of motor sequences (Awh & Gehring, 1999; Fan et al, 2007; Nolte, 2001; Turner et al., 2006). In general, a greater proportion of activity was documented in the left hemisphere for AWNS, while AWS displayed right hemisphere lateralization even during non-linguistic oral movements (Braun et al., 1997).

De Nil et al. (2000) reported analogous pattern in cerebral activation during oral single-word reading tasks. Although bilateral activation of both hemispheres was observed, cerebral activity was mainly lateralized to the left hemisphere in AWNS and to the right hemisphere in AWS. In AWNS, the left cingulate cortex, a region associated with memory and visual imagery displayed significant levels of activity. Interestingly, left hemisphere activation in AWS was restricted to the cuneus region which is also associated with visual imagery. The cuneus region encompasses the upper half of the primary visual cortex (Nolte, 2001). In the right hemisphere, the frontal motor cortex including the

dorsolateral prefrontal cortex (Brodmann Area 9 and 46) and the supramarginal cortex, which are associated with phonological encoding, were prominently activated in AWS. The dorsolateral prefrontal cortex which is associated with motor planning includes the right hemisphere homologue of Broca's area. The right lateralization of activity in AWS may imply greater reliance on the right hemisphere for linguistic processing. In addition, Watson et al. (1994) documented greater right activation in the middle temporal and inferior frontal regions of a subgroup of AWS who were identified as linguistically impaired. A similar observation was made by Foundas et al. (2003). In addition, the study by Foundas and colleagues reported a positive correlation between reduced prefrontal and occipital lobe volumes and linguistic deficits.

In addition to the cerebrum, anomalous lateralization has also been observed in the cerebellum. The cerebellum is involved in processing sensory information and motor control particularly, in timing and error correction of movement (De Nil., 2004; Nolte, 2001). During paragraph and single word readings, the cerebellum displayed bilateral or left-lateralized activity in AWS (De Nil et al., 2000; Fox et al., 2000). In AWNS, activity of the cerebellum was bilateral or right lateralized (Fox et al., 1996, 2000). Cerebellar activity was more widespread in AWS when compared to AWNS during fluent and disfluent speech (Fox et al., 2000).

Further, anomalous sequencing and delayed cerebral activation have also been reported using magnetoencephalography (MEG) technique. Salmelin et al. (2000) detected disparities between AWS and AWNS in the timing of cortical response prior to readings of visually presented single-words. In AWNS, the left inferior frontal region was activated prior to the motor cortex. A reversal in sequence was observed in AWS, in which activation of motor programming was antecedent to articulatory coding. In addition, Biermann-Ruben et al. (2005) reported delayed activation of the left Rolandic operculum

in AWS by 100 ms when compared to AWNS during word repetition. In AWS, the left Rolandic operculum is associated with reduced integrity of white matter (Sommer et al., 2002). In addition, activation of the right Rolandic operculum (right homologue of Broca's area) was restricted to AWS (Biermann-Ruben et al., 2005). Increased fluency was correlated with greater right frontal operculum activity (Preisbich et al., 2003). Interestingly, AWNS with left frontal opercular damage have been observed to recruit the right frontal operculum during tasks requiring its left hemisphere homologue (Raichle, 1996) which supports the hypothesis that the right frontal operculum may play a compensatory role in stuttering (Preisbich et al., 2003). These observations of atypical motor processing and delayed activation may be a consequence of hemispheric interference and/or reduced efficiency of the left hemisphere (Webster, 1990). In addition, impaired processing efficiency and performance may be a consequence of neural competition for resources (Perkins et al., 1991; Rastatter & Dell, 1987).

Results of these investigations suggest reversed dominance for speech processing in AWS, even in the absence of stuttering. In AWNS, speech processing occurs in the left hemisphere which is better suited to process segmental, time-dependent information such as language (Guitar, 2006). In contrast, speech processing in AWS occurs in the right cerebral hemisphere which is better suited for processing non-segmented, time-independent information including visuo-spatial processing (De Nil et al., 2003; Moore, 1984; Moore & Lang, 1977). Consequently, processing linguistic information in the right hemisphere will result in disfluency (Moore & Lang, 1977).

#### *Cerebral Activation following Fluency Treatment*

Temporary fluency methods, such as singing, have been shown to activate the left hemisphere, primary auditory and auditory association cortices in AWS which remain

inactive during speech production. These same areas are activated during speech and voice monitoring in Awns (Guitar, 2006). Fluency enhancing procedures purportedly reduce burden on the frontal areas and augment the sensory processing of the brain's posterior regions (Gordon, 2002). Following fluency treatment, several studies have reported decreased activation of the right hemisphere and increased activation in the left posterior frontal areas in AWS (Boberg et al., 1983; De Nil et al., 2003).

Changes in cerebral lateralization as indicated by increased alpha suppression of the left hemisphere following EMG biofeedback therapy have been documented (Moore, 1984). Post-treatment, AWS participants were more fluent and feature greater left hemisphere participation. Fluency techniques utilizing cancellation and speech rate modification have achieved similar results. Prior to treatment, AWS displayed greater disfluency and right hemisphere alpha suppression for speech and non-speech (visuospatial) tasks (Boberg et al., 1983). Boberg et al. postulate reduced inhibitory capacity of the left hemisphere as a basis for right hemisphere participation in linguistic processing in AWS. After treatment, AWS display reduced right hemisphere activation for speech tasks. As expected, activation patterns did not change for visuospatial tasks where greater right hemisphere participation was required.

Several other studies have also reported increased left hemisphere activation following fluency treatments that emphasize speech modification techniques including gentle onset, soft articulatory contact, syllable prolongation, etc. (De Nil et al., 2003; Giraud et al., 2008; Neumann et al., 2005). In a study of long- and short-term treatments of AWS, De Nil et al. (2003) reported overall reduction in the intensity of activity levels immediately following treatment. This reduction was most apparent in the region of the motor cortex. Additionally, greater distribution of activity was observed in the left hemisphere while right hemisphere activity became less widespread. This trend towards

reduced intensity and limited distribution within the right hemisphere was still apparent a year after treatment. The insula (which has been linked to articulatory planning) and the superior temporal gyrus which were strongly right lateralized prior to treatment, became left lateralized immediately following treatment (Prince et al., 2003). This shift in lateralization was still apparent a year after treatment. In contrast, cerebellar activity became right lateralized. Following treatment, increased activity in the cerebellum, and left frontal and temporal cortices were directly correlated with fluent speech. Increased activation of these regions is suggestive of greater sensory and motor monitoring of speech as a consequence of fluency techniques (De Nil et al., 2001). Although activation patterns were not identical to those of AWNS a year after treatment, a general reduction in intensity of activation and shift towards “normalized” pattern of activation were observed in AWS.

In addition to the observations made by De Nil et al. (2003), Neumann et al. (2005) documented reduced activity in the right frontal cortex, and increased activity in the left anterior cingulate cortex and in the region adjacent to the left Rolandic operculum. Reduced white matter integrity has been observed in the left Rolandic operculum (Sommer et al., 2002). Increased activation of the region adjacent to the left Rolandic operculum was still evident two years after therapy. Neumann et al. proposed that recruitment of neural resources in the vicinity of the left Rolandic operculum is probably linked to deactivation of its right homologue within the right frontal cortex. In other words, activations seen in the region adjacent to the left Rolandic operculum is a consequence of neural reorganization and/or compensation and is suggestive of neural plasticity in AWS, similar to those seen in stroke patients (Neumann et al., 2005). Areas that featured reduced activation prior to treatment including the left precentral and occipital regions were unaffected by the fluency treatment.



Stuttering has also been linked to basal ganglia disfunction specifically, affecting timing in speech production (Alm, 2004; Mulligan et al., 2003). The similarity between stuttering and disorders affecting the basal ganglia such as Parkinson's has further reinforced this hypothesis. Analogous to Parkinson's patients, external cues prompt fluent motor production in AWS (Giraud et al., 2008). In addition, Giraud et al. (2008) reported a positive correlation with activity in the caudate nucleus (which is part of the basal ganglia) and stuttering severity before fluency therapy. This correlation was not observed following fluency treatment. Activity levels of the caudate nucleus "normalized" after treatment, increasing in less affected AWS who displayed low levels of activity prior to treatment, and decreasing in more affected AWS who displayed higher levels of activation prior to treatment. The disparity in caudate activity is suggestive of differences associated with motor execution within the AWS group as a function of stuttering severity. In general, caudate activation has been observed to decrease in the initial stages of motor learning but increase after learning was completed and maintenance of the speed of movement was required (Giraud et al., 2008). For individuals with severe stuttering, fluency therapy required learning new motor sequences related to speech production while in individuals who were less severe complete re-learning was not necessary (Giraud et al., 2008). Evidence of right frontal opercular compensation was also reported by Giraud and colleagues. Prior to therapy, AWS who were more severely affected featured lower activation of the right frontal operculum than AWS who were less affected. Giraud et al. cites the lack of inhibitory control by Broca's area, its left hemisphere homologue as cause for activation of the right frontal operculum. The study by Giraud et al. did not present data related to the right frontal operculum after therapy.

Following treatment, a reduction in overall intensity of cerebral activation and greater distribution of activity in the left hemisphere regions associated with speech were

observed. The activation pattern in AWS following therapy suggests a shift towards more “normalized” lateralization of speech processing that favors the left hemisphere. The pattern of cerebral activation during fluent and disfluent speech before and after therapy suggests that stuttering is associated with anomalous cerebral laterality related to anatomy and activity that favors the right hemisphere. Consequently, these documented anomalies may be associated with atypical function (Foundas et al., 2003).

### **Stuttering and Functional Laterality**

Stuttering has also been linked to atypical auditory processing (Howell et al., 2006). Brady and Berson (1975) performed a dichotic listening experiment where AWS and AWNS participants listened to different syllables presented two seconds apart. They were then asked to select the syllable they heard from a list. Female AWS were the only participants (from a group comprising of AWS and AWNS of both sexes) who were less likely to present a right ear advantage. In addition, Blood and Blood (1989) reported a negative correlation between right ear advantage and stuttering severity. Foundas et al. (2004) also presented evidence for atypical auditory processing. Left-handed male AWS were found to have a left-ear bias in a non-directed attention task and were better at shifting auditory attention than AWNS. On the other hand, right-handed female AWS failed to show ear bias in either direction and were less successful at shifting attention. In contrast, Newton et al. (1986) reported a left ear bias in right-handed AWS. Differences in ear advantage among the AWS are suggestive of heterogeneity in the mode of auditory processing within the group. In addition, AWS group outperformed AWNS in left ear accuracy in two different test conditions: (1) when only two stimuli were presented concurrently and (2) during multi-stimuli presentation without overlap (Newton et al., 1986). The pattern of auditory advantage manifested by AWS suggests a link between the

atypical size and symmetry of the planum temporale and Heschl's gyrus (which are involved in auditory processing) and left ear advantage (Foundas et al., 2003). Further, moments of disfluency are associated with reduced activation of the auditory regions while fluent speech features greater activation of the same regions (Fox et al., 1996). Stager et al. (2003) also reported greater activation of the auditory regions in the left cerebral hemisphere during fluency evoking tasks and more bilateral activation under normal speech production conditions (Stager et al., 2003).

In addition to auditory processing, other indices of lateralization including visual processing have been investigated in stuttering. In unilateral tachistoscopic stimulation tasks, AWS did not differ from AWNS in displaying a right visual field advantage but required longer processing durations (Johannsen & Victor, 1986; Rastatter et al., 1987). However, AWS performed better than AWNS in left visual field identification (Johannsen & Victor, 1986; Rastatter & Stuart, 1995). Longer processing durations related to the left cerebral hemisphere (right visual field) and better performance associated with the right hemisphere (left visual field) are suggestive of reduced efficiency of the left hemisphere and/or greater dominance of the right hemisphere in AWS. As a consequence of interhemispheric processing, AWS may require longer processing times. Rastatter et al. (1987) postulates that in AWS written material is processed in the left hemisphere but final analysis of information is performed by the right hemisphere regardless of which side of the visual field was stimulated (Rastatter et al., 1987). Alternatively, the longer processing times required by the left hemisphere may not be due to reduced efficiency but its inability to inhibit right hemisphere participation. Sussman (1982) proposes that stronger lateralization of one hemisphere will reduce interhemispheric processing. Thus, participation of the right hemisphere may be indicative of reduced left hemisphere

dominance in AWS. These outcomes suggest AWS possess atypical cerebral organization and/or impoverished resources and consequently, display reduced processing efficiency.

Other attempts to assess hemispheric dominance and fluency in AWS have focused on handedness. In one of the earliest treatments intent on shifting cerebral dominance, Travis (1978) placed the left forearm and hand of AWS in a plaster cast to force the individuals to use only the right forearm and hand for tasks normally done with the left hand. Although the treatment did not reduce stuttering, it suggested a link between cerebral laterality and fluency. Recent studies into handedness suggest AWS have poorer bimanual coordination, and reduced writing quality (Fitzgerald et al., 1984; Greiner et al., 1986a, 1986b; Vaughn & Webster, 1989; Webster, 1988; Zelanik et al., 1997). AWS also presented more mirror reversals for writing, diminished left hand organization and greater discrepancy between left and right hand performances than AWNS (Fitzgerald et al., 1984). When asked to write numbers concurrently with both hands, right-handed AWS demonstrated more mirror reversals with their left hand than their right hand. Mirror reversals were not observed in AWNS. In addition, the left hand of AWS produced writings that were less aligned and less legible when compared to the performance of their right hand and AWNS (both hands). A similar trend was observed in non-handwriting functions. Vaughn and Webster (1989) tested bimanual manipulation of right-handed individuals in common tasks such as dealing cards, dialing a telephone and removal of nut from bolt. AWS were slower than AWNS in all tasks. The most significant difference was detected during the nut and bolt exercise where participants were asked to rotate and remove the nut without turning the shaft. The left hand performance was not significantly different for both groups. However, the right hand performance of AWS was significantly slower than AWNS. The right hand performance of AWS during bimanual writing and manipulation Webster (1990) suggests the reduced capacity for concurrent motor

processing is a product of interhemispheric interference and/or reduced efficiency of the left hemisphere.

In a bimanual coordination task requiring concurrent tapping of the index finger of both hands, AWS performance was not significantly different from AWNS (Hulstijn et al., 1992). In contrast, during bimanual coordination requiring synchronous speech production and finger tapping, AWS demonstrated poorer coordination when compared to AWNS (Hulstijn et al., 1992). For the speech and finger tapping task, participants were required to vocalize the word “pip” and tap the index finger of their dominant hand in synchrony. The reduced coordination demonstrated by both right-handed ( $n=11$ ) and left-handed ( $n=1$ ) AWS maybe suggestive of reduced left hemisphere efficiency for dual processing particularly, when speech is involved. In AWNS, both the right index finger tapping and speech processing tasks were left hemisphere lateralized. Alternatively, AWS may process finger taps in the left hemisphere and speech in the right hemisphere. The interhemispheric processing or interference from the right hemisphere may result in reduced coordination.

In addition, aspects of bimanual coordination involving the feet have also been examined in AWS. When asked to tap fingers in tandem with the foot, AWS failed to display the same right foot bias observed in AWNS (Forster & Webster, 1991). The finger tapping performance of AWS was similar with either left or right foot movements. For AWNS, left foot tapping was more disruptive to finger movements than right foot taps. The pattern of foot interference demonstrated by AWS may be indicative of a weak preferential rightward attention shift or a weak left hemisphere lateralization when compared to AWNS (Bishop, 1990).

The results of these studies indicate that AWS appear to be less efficient than AWNS in non-speech processing that requires left hemisphere participation, but in requisite right hemisphere events, AWS appear to be equally skilled or more efficient than

AWNS. The atypical functional performance observed in AWS maybe a manifestation or consequence of anomalous cerebral architecture and/or activation (Foundas et al., 2003).

### **EMG and Stuttering**

EMG has played an important role in stuttering research. The methodology involves a relatively non-invasive procedure and accordingly, has also been utilized as a treatment tool to promote the reduction of muscular activity as stuttering has been associated with abnormally high muscle activity (de Felicio et al., 2007). Stuttering is often regarded as a corollary of aberrant speech muscle coordination (McClean & Tasko, 2004). In line with that hypothesis, numerous EMG studies in stuttering have been devoted to examination of speech musculature, particularly the larynx, jaw, tongue and lips. The larynx has been cited as the locus of breakdown in stuttering (Freeman, 1977, as cited in Freeman, 1979; Freeman & Ushijima, 1978; Gautheron et al., 1973; Wyke, 1969). Poor voice quality, abnormal prosody and timing have been ascribed to abnormal laryngeal behavior in AWS (Van Riper, 1982). Three key anomalies are associated with the larynx during a moment of disfluency: (1) disproportionately high levels of muscle activity (2) incongruous eruptions of activity and (3) atypical abductor-adductor coordination (Freeman, 1977, as cited in Freeman, 1979; Freeman & Ushijima, 1978; Shapiro, 1980). Naturally (although controversial), the treatment of stuttering has included the reduction of laryngeal tension via EMG biofeedback (Guitar, 1975; Hanna et al., 1975; Hasbrouck & Lowry, 1989; Moore, 1984; Prosek et al., 1978).

EMG research has also examined mandibular muscles. Several studies contend that mandibular tremor observed during moments of stuttering is a result of muscle contractions generated in attempt to produce speech and is similar to those produced in other muscle systems (McClean et al., 1984; Platt & Basili, 1973). Lanyon et al. (1976) were able to reduce masseter muscle activity in six AWS during approximately 18 hours of training.

The reduction in EMG activity was correlated with increased fluency for short utterances. Platt and Basili performed an EMG examination of three AWS with discernible mandibular tremor during moments of stuttering. Results indicated elevated EMG signals during both stuttered monosyllabic and multisyllabic utterances, as well as during non-speech jaw opening/closing maneuvers. In addition, Sheehan and Voas (1954) (as cited in Bloodstein, 1987) found the EMG signal to increase and peak toward the end of a stutter (Sheehan & Voas, 1954, as cited in Bloodstein, 1987). Travis (1934) found asynchronous levels of jaw muscle activation during moments of stuttering, whereby an increase of activity on one side of the jaw was accompanied by a decrease in activity at the opposing side.

The role of the tongue in a variety of speech disorders has a long documented history. The term “tangled-tongue” is often used to describe stuttering (Carlise, 1985). Therefore, it is not surprising that in the search for the etiology of stuttering the role of the tongue has been evaluated. More recently, aberrant levels of tongue activity were identified by Shapiro (1980) who recorded excessively high EMG levels in the *longitudinalis superior* muscle (i.e., an intrinsic muscle of the tongue). In general, moments of stuttering are found to correlate with exceptionally high levels of tongue activity (Freeman, 1977 as cited in Shapiro, 1980; Thurmer et al., 1983 as cited in Bloodstein, 1987).

Elevated levels of EMG activity have also been recorded in the lip muscles of AWS (van Lieshout et al., 1993). Code (1979) examined moments of stuttering in AWS compared to pseudo-stuttering produced by AWNS and found larger amplitude and longer durations of EMG activity during the stutter of an AWS than during a pseudo-stutter produced by AWNS. However, EMG amplitude and duration were indistinguishable during fluent passage reading between AWS and AWNS. van Lieshout et al. (1993, 1996a) examined fluent speech in AWS and likewise, reported longer EMG durations, higher

amplitudes and increased latency compared to AWNS speakers. Interestingly, periods of silence were also correlated with high levels of EMG signals in AWS (Shapiro, 1980). These results suggest lower muscle restraint and/or lower threshold for stimulation in AWS (Starkweather, 1995; McClean, 1996).

Discoordination and mis-sequencing of the lip muscles has also been detected in AWS. Lip muscles were activated in reverse order with the lower lip activated prior to the upper lip (Hulstijn et al., 1992; van Lieshout et al., 1996b). AWS displayed slower movement onset for both the lower and upper lips, and featured longer duration between lip onset and peak EMG activity in comparison to AWNS (Hulstijn et al., 1992; van Lieshout et al., 1996b). In addition, AWS demonstrated more variability in duration between voice onset and onset of lower lip movement (Janssen et al., 1983). Within the lower lips, the *depressor labii inferioris* (DLI) was activated earlier than the *depressor anguli oris* muscle (DAO), a reversal of the pattern seen in AWNS (Guitar et al., 1988).

In general, investigations into stuttering coupled with EMG concur on three major findings during or prior to a moment of stuttering: (1) elevated levels of muscle activity in various speech musculature (2) longer durations of muscle activity and (3) atypical muscle behavior compared to AWNS.

### **EMG and Laterality in Non-Stuttering Groups**

Handedness and language ability are two of the most prominent expressions of laterality<sup>3</sup> (Corballis, 2003; Sainburg, 2005; Sun & Walsh, 2006). Hand preference usually for the right, is present as early as 12 to 27 weeks gestational age (Knecht et al., 2000; McCartney & Hepper, 1999; Sun & Walsh, 2006). About 90% of individuals are right-

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<sup>3</sup> The right shift theory (Annett, 1972) proposes that cerebral dominance and handedness are affected by the right-shift gene (RS+). RS+ inhibits right hemisphere dominance for language and favors right-handedness. Accordingly, handedness and cerebral organization in individuals without RS+ develop by chance.



handed in terms of preference and dexterity with language and praxis functions lateralized to the left hemisphere; and visuospatial and attentional functions lateralized to the right (Rosenfield, 1980; Beaton, 1985; Hervé et al., 2006). Surprisingly, 27% of left-handed individuals have cerebral lateralization similar to right-handed individuals (Van Agtmael et al., 2003). In contrast, only 4% of right-handed individuals have right cerebral dominance similar to left-handed individuals (Van Agtmael et al., 2003). Bishop (1990) and Corballis (2003) propose that increased motor skills resulted from lateralized function of the hand. Sainburg (2005) furthers the proposal by suggesting that the cerebral hemispheres and their contralateral limbs are dedicated to different but specific functions. When comparing hand responses, Sainburg found the non-dominant arm to be better adapted to load compensation and reaching the target location. The dominant arm overcompensated for added weight, was significantly less precise in final positioning but better at sustaining velocity and trajectory of movement. In short, the left cerebral hemisphere is adapted for motor precision and movement velocity, while the right hemisphere is better at spatial tasks and motor functions in right handed individual (Haaland & Harrington, 1996; Sadeghi et al., 2000). Hemispheric specialization and accordingly, hemispheric lateralization enhances motor skills and processing by expanding the neural resources available (Maupas, 2002; Sainburg, 2005).

In addition to hand usage, lateralization has also been observed for cognitive processing which is postulated to maximize the neural resources available. Diekhoff et al., (1978) postulated that the reduction of extraneous activity as a measure of cognitive processing can be observed in limbs which are contralaterally innervated. In support of their hypothesis, the right arm presented significant reduction in muscle activity during verbal recognition processing executed by the left hemisphere. Similarly, during facial recognition processing executed by the right hemisphere reduced muscle activity was seen

in the left arm. EMG levels were quantified against the baseline measurement of muscle at rest. Even in the absence of overt cognitive or motor processing, muscle potentials (at rest) were lateralized. Ruggieri and Sabatini (1982) examined the resting muscle potential in 40 self-reported right-handed females. Despite a right hand preference (and consequently left hemisphere dominance), about 52.5% of participants exhibited a larger resting potential on the left side of the neck, wrist, and face. About 40% evinced larger resting potential on the right and only 2% did not show muscle dominance on either side. In contrast, Schwartz et al. (1979) reported overall higher resting potential on the left than right side of the face in a study which included equal number of right-handed male ( $n=10$ ) and female ( $n=10$ ) participants. The results of these studies suggest that muscle resting potential may be related to gender, with males displaying larger resting potential on the left side of the face. In general, male faces are larger on the left while female faces are larger on the right (Schmidt et al., 2006). Interestingly, muscle potential recorded from the right dominant individuals was greater than the muscle potential recorded from left dominant individuals. Disparities in resting potential may be related to differences in neural input to the corresponding muscles (Gabriel et al., 2006).

One of the most intriguing issues to arise from EMG studies is the notion of laterality and facial expressions. Darwin is credited with the first study on facial asymmetry of expression. His impetus was the phenomenon of the one-sided human sneer which he equated to a dog baring its teeth (Fridlund, 1988). Current studies on facial asymmetry are based on the principle of cerebral involvement. The Right Hemisphere Hypothesis states that the right cerebral hemisphere is dominant for emotional expression (Borod et al., 1988). The Valence Hypothesis makes a distinction between positive and negative emotions with the right hemisphere controlling the expression of negative emotions and left hemisphere controlling the expression of positive emotions (Davidson,

1992; Davidson et al., 2000). In other words, during the expression of negative emotion, a person would exhibit greater emphasis in the left side of the face. Positive emotion would be exhibited in greater emphasis on the right side of the face.

Dimberg and Petterson (2000) required 16 right-handed males and an equivalent number of right-handed females to view happy and sad faces. Their passive reactions to the images were recorded from the left and right *corrugator supercilii* muscle (CS) and *zygomatic major* muscle (ZM) of their own faces. Happy faces were found to elicit larger muscle activity at the ZM, while angry faces produced a larger response from the CS. The CS muscle, which is involved in drawing down the eyebrows is also known as the “grief muscle” (Sirota & Schwartz, 1982). The left side of the face recorded greater levels of muscle activity for both happy and sad faces. Zhou and Hu (2006) measured ZM and CS activity from participants (11 right-handed males & 26 right-handed females) asked to physically express happy or sad faces. Happy poses induced the largest muscle activity at the left ZM. Sad poses generated the largest EMG activity in the left CS. Both studies (Dimberg & Petterson, 2000; Zhou & Hu, 2006) confirm the Right Hemisphere Hypothesis for expression of emotion. That is, regardless of the type of emotion, the left side of the face is most active. Alternatively, results from Schwartz et al. (1979) tend to support the Valence Hypothesis. Facial lateralization was found to be dependent upon type of emotion. Larger right facial muscle or left cerebral activation was perceived for positive emotion, while negative emotion was lateralized to the left facial muscles or right cerebral hemisphere.

Unlike the upper facial muscles which are bilaterally innervated, the lower facial muscles are contralaterally innervated, with the largest group associated with the mouth (Graves et al., 1982; Martini, 2006). Therefore, evaluations of cerebral lateralization and facial asymmetry must incorporate lower facial muscles including those of the lips

(Thompson, 1982). Laterality of mouth movement during speech is an observable phenomenon even to the untrained eye and can be substantiated by EMG. Mouth asymmetry is directly correlated with the degree of hemisphere participation (Cacioppo & Petty, 1979; Graves & Landis, 1990). Wohlert and Larson (1991) recorded a subtle pattern of earlier movement onset for the right versus left lip during lip protrusion. In addition, Wohlert and Hammen (2000) recorded greater right than left lip activity during reading. Contralateral innervation of the lip muscles by facial nerve VII suggests that greater right mouth opening bias and muscle activity is a consequence of larger left cerebral hemisphere contribution and vice versa (Graves et al., 1982; Graves & Potter, 1988; Graves & Landis, 1990; Martini, 2006). Differences in muscle activity were even more pronounced with fast, loud and precise articulations. In addition to the left-right asymmetry of lip activity, differences between the upper and lower lips have also been reported. Wohlert and colleagues documented greater levels and more continuity of activity in the lower lips than the upper lips (Wohlert & Goffman, 1994; Wohlert & Hammen, 2000). Wohlert and Hammen propose that muscles in the lower lips are associated with lip opening and closing while muscles of the upper lips are associated with lip closing and rounding, thus, greater continuity of activity can be observed in EMG signals recorded from the muscles of the lower lips. The observations made by Wohlert and colleagues substantiate other investigations suggesting that the upper and lower lips are organized into non-overlapping quadrants under distinct neural control even during coordinated events (Abbs, & Gracco, 1984; Goffman & Smith, 1994; Gracco & Abbs, 1985; McClean, 1996).

There is a growing body of research that has examined the link between speech and emotion (Batliner et al., 2008; Busso & Narayanan, 2007; Egloff et al., 2006). Speech is assumed to carry information about a person's attitude and stress level (Lazarus, 1999; Wichmann, 2000). Cast within the framework of laterality and facial expression, the EMG

results obtained for speech production do not easily fit the Right Hemisphere Hypothesis. In contrast, if speech is linked to emotion, the results for speech production may fit the Valence Hypothesis. Assuming speech production is typically associated with positive emotion, such emotion would be evident on the right side of a speaker's face. Interestingly, there are reports that "full blown" emotion competes for control with the cognitive system that underpin fluent speech (Cowie & Cornelius, 2003).

### **EMG and Laterality in Stuttering Groups**

Past research examining a wide range of anatomical and physiological parameters has found AWS to differ from AWNS. Specifically, research examining various aspects of cerebral laterality in AWS has shown: (1) (over)activation of the right hemisphere, (2) deactivation of auditory areas, (3) rightward or lack of asymmetry in the planum temporale and (4) increased white matter in the right hemisphere. These results would seem to confirm that AWS differ from AWNS at the "highest" level of speech organization and production. While there is evidence to suggest that peripheral motor system (e.g., limbs) are also indicative of laterality differences between AWS and AWNS, there has been little research examining laterality in the peripheral speech structures. That is, are laterality differences observed between AWS and AWNS present at the "lowest" level of speech organization and production?

The suggestion of laterality differences between AWS and AWNS near the end point of the speech chain is evident in EMG research. These studies found AWS to show (1) increased EMG activity, (2) longer periods of EMG activity, (3) delayed movement onset and (4) asynchronicity of muscle coordination compared to AWNS. While there is a great deal of research examining EMG and, by the same token, cerebral laterality in AWS, there have been few attempts to determine whether the laterality found at higher levels of

speech organization are also present in the anatomical structures directly involved in speech production, specifically the lips. Lip laterality associated with cerebral lateralization can be ascertained non-invasively at the moment of speech production via EMG. Accordingly, the research question posed in the present study was, “*Do AWS differ from AWNS in the laterality of lip EMG signals?*”

In addition, there have been few attempts to consider the possible influence of emotion as a contributing factor to cerebral laterality differences between AWS and AWNS. This is particularly striking as negative emotion has been cited as a component of the stuttering experience (Craig et al., 2003; Ezrati-Vinacour & Levin, 2004). Szelag et al. (1997) investigated the link between neuroticism and cerebral laterality in adolescents who stutter. The study reported better performance of the right hemisphere in adolescents without stutter and moderately neurotic adolescent with stutter during a facial recognition test. In contrast, highly neurotic adolescents who stutter displayed better performance with their left hemisphere for a task typically associated with the right hemisphere. The results of this study suggest cerebral laterality may be influenced by the state of emotion. Based on past research examining laterality in AWS and AWNS, as well as research examining laterality in facial expression, a test of the two laterality hypotheses was performed. The Right Hemisphere Hypothesis states that the right cerebral hemisphere is dominant for (all) emotional expression. Assuming speech production arouses an emotional response, this hypothesis would predict that both AWS and AWNS would show greater EMG lip activation on the left side of the face. However, if AWS demonstrate stronger emotional expression with speech as a result of their stuttering, it is also possible that the AWS may show greater EMG lip activation on the left side of the face compared to AWNS.

Alternatively, the Valence Hypothesis makes a distinction between positive and negative emotions with the right hemisphere controlling the expression of negative

emotion and the left hemisphere controlling the expression of positive emotions (Davidson, 1992; Davidson et al., 2000). Brain imaging studies have further demonstrated activation of the right prefrontal regions of the cerebral hemisphere for negative emotions (Erk et al., 2007). Assuming speech production among AWS is generally associated with negative emotion, the Valence Hypothesis would predict that AWS would show greater EMG lip activation on the left side of the mouth, while AWNS would likely show greater lip EMG activation on the right side of the mouth.

### Statement of problem

Stuttering is associated with anomalous cerebral laterality that favors the right. To date, research into stuttering has revealed differences in anatomy, neural activation and speech movements between AWS and AWNS (De Nil et al., 2000; Jancke et al., 2004; Moore & Lang, 1977; van Lieshout et al., 1993). These studies indicate that the perceived discrepancies translate into speech production even though the speech differences may be qualitatively undetectable by the listeners. One might expect these differences to originate somewhere between the neuromuscular pathways of the formulation and production of speech. Past research has suggested that the brain of AWS and AWNS are activated differently during speech tasks (Wells & Moore, 1990). Past studies have reported elevated muscle activity in AWS even in absence of overt movements (Shapiro, 1980). In addition, although differences between AWS and AWNS may present prior to the onset of speech movement, these differences are not expected to reach significance until actual speech production (van Lieshout et al., 1993). EMG offers a non-invasive procedure to investigate the neural organization at the moment of speech production (de Felicio, 2007; Fridlund, 1988; Hof, 1984). Since muscle movement is thought to provide an estimate of central nervous system contribution (Hoehn-Saric et al., 1997), the present study utilized EMG, as it offered a reliable documentation of muscle activity that may be visually indiscernible (Cacioppo & Petty, 1979, 1981; Magneé et al., 2007). Given current findings on cerebral laterality and functional asymmetry, the current study examined lip laterality in AWS as a measure of cerebral activation and also considered the links between speech production and emotion within the confines of the Right Hemisphere Hypothesis and Valence Hypothesis of facial expression. The general research question explored was, *“Do AWS differ from AWNS in the lip muscle activation surrounding speech and nonspeech movements?”*



## Method

### *Participants*

*AWS Participants.* Five right-handed male AWS were recruited for participation in the project. The general characteristics the AWS participants are listed in Table 1. The AWS participants ranged in age from 21 to 30 years, with a mean age of 26 years. Participants were recruited through local media advertisements, stuttering support groups, as well as directly contacting clients receiving speech therapy at the University of Canterbury. Initial criteria for inclusion were the presence of stutter-like disfluencies (SLDs), which was determined by a 300-word conversational speech sample. Single syllable word repetitions, part-word repetitions, prolongations, blocks, and broken words were considered to be SLDs (Ambrose & Yairi, 1999). Other disfluencies (ODs) consisted of phrase repetitions, interjections, and revisions. The percentage of overall disfluency ranged from 7% to 37% and averaged 10% for the group. According to the Stuttering Severity Instrument (SSI) (Riley, 1994), two participants presented with very mild stuttering, another two presented with mild stuttering and the remaining participant presented with moderate stuttering. All participants reported receiving formal therapy for their stuttering at various points in their lives. Only one participant was currently receiving treatment for stuttering at the time of data collection. All participants were paid for their involvement in the project.

Handedness for each AWS participant was ascertained according to the Edinburgh Handedness Inventory (Oldfield, 1971). The handedness laterality quotient for the AWS participants ranged from 60 % to 100%. A copy of the revised Edinburgh Handedness Inventory questionnaire is provided in Appendix I. Footedness of participants was also determined. Footedness has been suggested to be a better predictor of language lateralization than handedness (Elias & Bryden, 1998). All participants indicated a right

Table 1. General characteristics of the adults who stutter (AWS). The table includes sex, age, handedness score, stuttering severity based on the SSI (Riley, 1994), percent disfluency, footedness, history of speech therapy, family history of stuttering, and age of stuttering onset.

AWS Participants									
Participant	Sex	Age	Handedness*	SSI and (Score)	Percent Disfluency	Footedness	History Speech Therapy	Family History	Age of Onset
1	Male	30	100%	mild (20)	7%	Right	Yes	Yes	5 y.o.
2	Male	29	60%	very (6) mild	8%	Right	Yes	Yes	6 y.o
3	Male	26	100%	very (15) mild	13%	Right	Yes	Yes	2 y.o
4	Male	24	100%	moderate (24)	37%	Right	Yes	Yes	pre-school
5	Male	21	60%	mild (21)	10%	Right	Yes	No	pre-school

\* all participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971).

foot preference. Participants were also requested to fill in a questionnaire related to their background. A copy of the background questionnaire is provided in Appendix II. AWS participants were judged as free of neurological and health problems based on personal report. In addition, all AWS participants regarded speech production as a relatively negative experience.

*AWNS Participants.* Five right-handed male AWNS participants served as controls. The general characteristics the AWNS participants are listed in Table 2. The participants were matched to the AWS participants to within five-years of age. The age range of the AWNS group was 21 to 32 years with a mean age of 25 years. Participants were recruited from students enrolled in various Psychology classes at the University of Canterbury and paid for their involvement. The handedness laterality quotient for AWNS participants ranged from 88.2 % to 100%. All participants indicated a right foot preference except for an individual with a left foot preference. Participants were also requested to fill in a questionnaire related to their background. A copy of the background questionnaire is provided in Appendix II. AWS participants were judged as free of neurological and health problems based on personal report. In addition, all AWNS participants viewed speech production as a relatively positive experience.

The study was approved by the University of Canterbury Human Ethics Committee and all participants provided informed written consent. A copy of the consent form is provided in Appendix III.

### ***Equipment and Electrode Placement***

The present study utilized surface EMG as a measure of central nervous system (CNS) motor output for muscle activity and coordination (Frigio et al., 2000; Zwarts et al., 2000). The EMG signals were recorded with miniature Au/AuCl disk electrodes using the NeuroScan SynAmps<sup>2</sup> system (Compumedics, 2003). Miniature surface electrodes were

Table 2. General characteristics of the adults who do not stutter (AWNS). The table includes the sex, age, handedness, footedness, history of speech therapy of each participant, and family history of stuttering.

AWNS Participants						
Participant	Sex	Age	Handedness*	Footedness	History of Speech Therapy	Family History
1	Male	32	100%	Right	No	No
2	Male	29	88.9%	Right	No	No
3	Male	21	100%	Right	No	No
4	Male	21	100%	Left	No	No
5	Male	21	88.2%	Right	No	No

\* all participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971).

selected as they offer less obstruction to movement compared to larger electrodes (Lapatki et al., 2003). Additionally, smaller electrode dimensions have been found to reduce inter-electrode distance and thus increases muscle selectivity (Cole et al., 1983, as cited in Blair & Smith, 1986; Lapatki et al., 2003). Impedances and noise at the metal-skin junction were reduced by abrasion with Nuprep™ to remove any dead skin and oil residues (Gerdle et al., 1999). Electrode impedances were maintained at 5 k $\Omega$  or lower.

Following the method by Wohlert and Hammen (2000), electrodes were placed around the perimeter of the mouth to identify muscle action potential associated with the *obicularis oris inferior* (OOI) and *obicularis oris superior* (OOS) muscles. Surface electrodes were placed in pairs in four quadrants at the: (1) left upper lip (LU), (2) right upper lip (RU), (3) left lower lip (LL), and (4) right lower lip (RL). Each pair of bipolar electrodes was placed approximately 1 cm apart, centered within each quadrant, and positioned as close as possible to the vermilion border of the lips parallel to the muscle fiber direction (Gerdle et al., 1999; Lapatki et al., 2003). Bipolar electrodes were used as they offer increased spatial resolution and improved signal-to-noise ratio (SNR) (Gerdle et al., 1999; Roeleveld et al., 1998). All electrodes were referenced against the forehead (Schwartz et al., 1979; Wohlert & Smith, 2002). A ground electrode was placed on the right earlobe (A2) (Cacioppo & Petty, 1979; Platt & Basili, 1973). The electrodes were attached to sites using Ten20 conductive paste and fastened to the skin with surgical tape. An illustration of the various electrode placements is provided in Figure 1. In addition to the EMG signals, an audio recording was obtained for all speaking behavior. A tabletop dynamic microphone (DSE PC Desktop) was situated approximately 25 cm away from the participant's mouth.

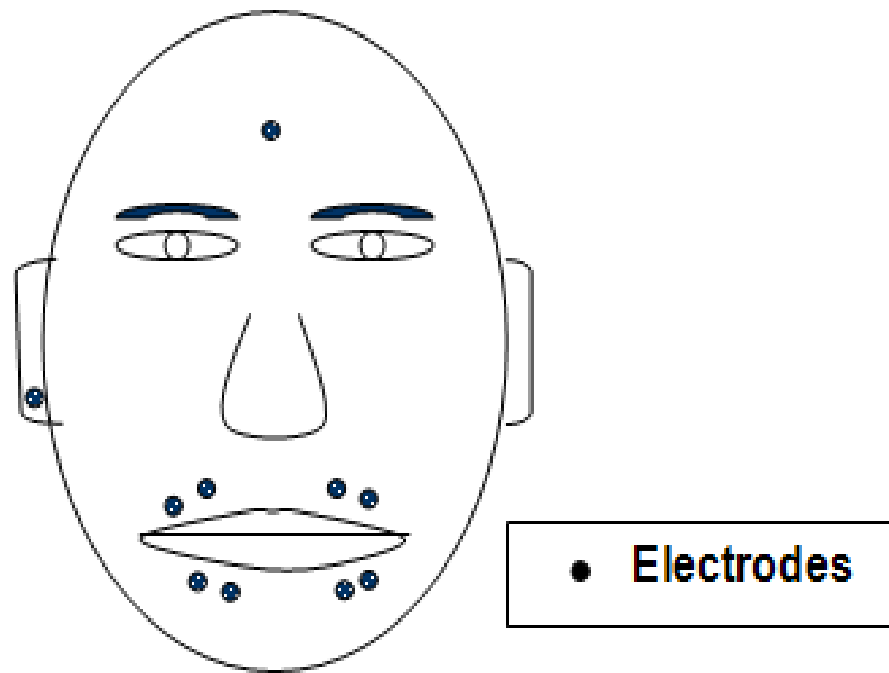


Figure 1. Idealized location of the electrode placements for recording of surface electromyographic (EMG) signals along the *obicularis oris inferior* (OOI) and *obicularis oris superior* (OOS) muscles. The pairs of bipolar EMG electrodes were situated approximately 1 cm apart along the vermillion border of the lips and centered within the quadrants of the: (1) left upper lip (LU), (2) right upper lip (RU), (3) left lower lip (LL), and (4) right lower lip (RL). All electrodes were referenced against the forehead. A ground electrode was attached to the right earlobe (A2).

### ***Speech and Non-speech Samples***

*Speech Samples.* Lip muscle activity was examined in two fluent single-word production tasks and one oral reading task<sup>4</sup>. The word production tasks examined (1) /f/ single-word production, (2) /p/ single-word production and (3) single-sentence reading. For each single-word production task, participants were required to name aloud pictures showing items that when vocalized started with the word-initial /f/- or /p/- phoneme. The particular phonemes were selected because they represented variations in place and manner of articulation, as well to ensure lip movement. All pictures were presented in color. A total of four different pictures were recycled for the speech tasks (two /f/-pictures & two /p/-pictures). The pictures used for elicitation of single-word naming included, *fish*, *four*, *pig* and *purse*. Copies of the pictures are presented in Appendix IV. Each picture was produced five times for the picture-naming tasks, resulting in 20 single-word productions (10 /f/ productions & 10 /p/ productions). The oral reading task involved production of the first line of the Grandfather Passage (Darley, Aronson, & Brown, 1975), *You wished to know all about my grandfather*. The same phrase was sampled by Wohlert (1993). All sentences were read at a normal reading rate.


*Non-speech Samples.* One non-speaking task was included in this study. The task was similar to the procedure used by Wohlert (1993). Participants were asked to purse their lips together as the way they would when saying the word “pool”. There were a total of 20 lip pursing trials collected from each participant.

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<sup>4</sup> Originally, it was assumed that moments of perceived natural stuttering might occur during the speech production tasks. If so, these moments were to be analyzed separately from the fluent speech samples. However, no moments of stuttering occurred during the sampling period. Therefore, the samples analyzed in the present study were all perceived to be produced fluently.

### ***Data Collection Procedures***

Prior to collection of the speech and non-speech samples, participants were seated in a relaxed position approximately one-half meter from a laptop computer. Instructions were presented to each participant on the computer screen. The instructions were as follows:

*“Keep your facial and lip muscles relaxed. Focus on the white dot. When a picture appears, name the picture on the screen. Do not move your head or make any sudden movements prior to or during vocalization. There will be a 10s break between the picture-naming tasks. When you see a pair of lips , purse your lips as you would when saying the word “pool”. Read the sentences at your normal speaking rate”.*

Presentation of instructions was followed by a short practice session lasting approximately 5 minutes that reflected the ensuing tasks. The participants were free to ask for clarification of the instructions. Participants were shown the list of /f/-words and /p/-words prior to data collection so as to ensure uniformity of responses and familiarity with the speech stimuli.

At the onset of data collection, a 1 cm diameter white circle against a black background was displayed on the computer screen. Participants were asked to fixate their eyes on the circle. Following an approximately 3 second period of time, one of four options would appear on the screen (1) a /p/-picture, (2) a /f/-picture, (3) the Grandfather Passage, or (4) a “lip pursing” symbol. At the completion of each task, the white circle would reappear on the computer screen to ready the participant for the next (non)speech task. During this period, participants were instructed to relax their lips and facial muscles. Participants were reminded not to speak, or initiate any sudden movements prior to each task. All tasks were presented in randomized blocks. Each block consisted of either two



picture-naming tasks, or four lip pursing tasks, or a single sentence reading. A ten second break followed each block. In total, the (non)speech samples collected from each participant consisted of 20 picture-naming tasks, 20 lip pursing tasks and five single-sentence readings.

### ***Signal Processing***

Lip activity was recorded on EMG bipolar channels with a low pass of 200Hz and a high pass of 1Hz with an AD rate of 1000. All signals (EMG and audio) were recorded with a notch filter of 50Hz, digitized at 10K and stored on a computer hard drive. A typical display of the filtered, rectified and smoothed signals collected in the present study is provided in Figure 3. All EMG channels including audio were filtered offline with a bandstop between 145 Hz to 155 Hz. The audio signal was additionally filtered with a highpass filter of 70 Hz.

The EMG signals were measured using the MEP Analysator program which is designed to measure the peak amplitude of the waveforms recorded for each speech token (O'Beirne, 2008). For each participant, the peak EMG amplitude was determined for the following conditions:

- 1) /f/ single-word picture naming
- 2) /p/ single-word picture naming
- 3) Single-sentence reading (Grandfather passage)
- 4) Lip pursing (non-speech task)

Each EMG signal was individually displayed on a computer monitor. The signals were similar to the example provided in Figure 2. To measure peak EMG, a pair of vertical cursors was superimposed on the EMG waveform. The peak EMG value was determined as the highest amplitude between the point of initial break from baseline of the EMG signal to the point at which the signal returned to baseline. EMG peak was measured for LU, RU,

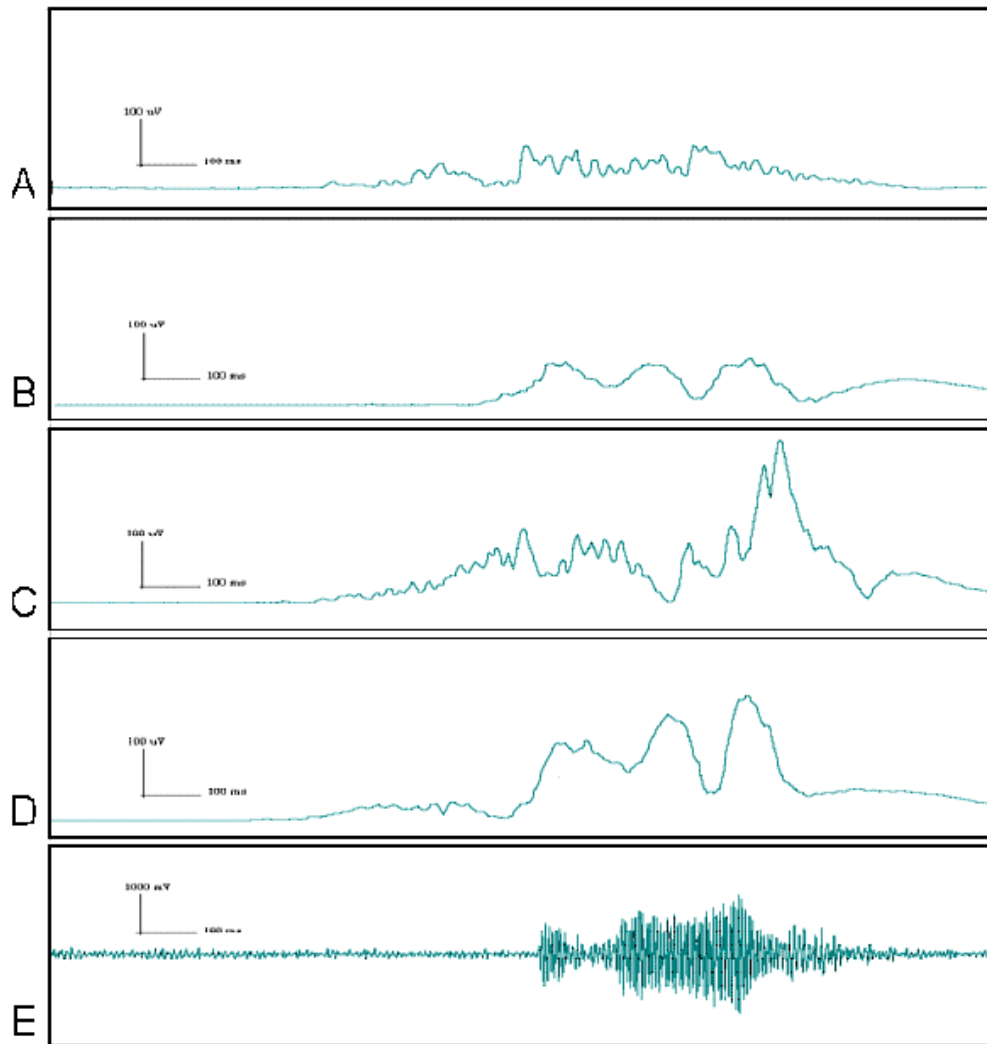


Figure 2. Typical display of the rectified and smoothed electromyographic (EMG) and audio traces obtained for single-word production recorded from an adult who does not stutter (AWNS). Panels A and B reflect the left upper (LU) lip and right upper (RU) lip EMG signals, respectively. Panel C and D reflect the left lower lip (LL) and right lower (RL) lip EMG signals, respectively. Panel E is the corresponding audio signal for the /p/-word.

LL and RL sites for each word, lip purse, and overall sentence production. EMG peak is presented in microvolts ( $\mu V$ ). For each (non)speech condition, the representative peak amplitude of each lip quadrant was derived from the median of measured peak values. For example, for the /f/-word production, the peak EMG value for the LU quadrant was the median obtained from a total of 10 single /f/-word tokens.

### ***Statistical Analysis***

A combination of descriptive and parametric statistics was employed to evaluate the individual and group results. The upper and lower lips were analyzed separately because several studies have suggested that the upper and lower lips are organized in non-overlapping quadrants under distinct neural control even during coordinated events (Abbs, & Gracco, 1984; Goffman & Smith, 1994; Gracco & Abbs, 1985; McClean, 1996; Wohlert & Goffman, 1994). Hence repeated-measures ( $2 \times 2 \times 2$ ) ANOVAs were performed to determine if there were differences in EMG amplitudes. The between-group factor was fluency condition (AWS & AWNS) and the within-group factors were “left side versus right side” and “upper lip versus lower lip”. In addition, a series of Pearson Product-Moment correlation coefficients were calculated to determine the strength of association for all possible pairings of the bipolar electrode placements: LU-RU, LU-RL, LU-LL, LL-RU, LL-RL and RU-RL.

### ***Reliability***

Reliability for the measurement of EMG amplitude was performed on 100% of the data set. The peak amplitudes for every token were re-measured and compared to the original measurements. Additionally, median values were determined for the samples and compared to the original set of median values. The reliability measurement for EMG latency was 100% that is, the correlation was perfect. Accuracy for the peak measurements and median values were determined by reanalyzing 100% of data.

## Results

### *Speech Production Tasks*

*Single /f/-word production.* The results for the peak amplitude of /f/-word production are listed on Table 3. There was considerable variability in peak amplitude between individuals within each group. Within the AWS group, individual peak amplitudes ranged from 4.41  $\mu$ V (AWS 2) to 297.65  $\mu$ V (AWS 3). For AWNS, individual peak amplitudes ranged from 4.68  $\mu$ V (AWNS 3) to 484.88  $\mu$ V (AWNS 2). For the AWS group mean amplitude, the EMG values across the four lip locations ranged from 11.23  $\mu$ V (RL) to 79.36  $\mu$ V (LL). For the AWNS group mean amplitude, the EMG values ranged from 23.18  $\mu$ V (LL) to 131.27  $\mu$ V (RL). In order to evaluate whether the peak EMG amplitudes differed between the two speaking groups across lip locations, a 2 x 2 x 2 (AWS versus AWNS; left upper lip versus right upper lip; left lower lip versus right lower lip) ANOVA was initially performed. The main effect of group (AWS versus AWNS) [ $F(1, 8) = 0.32, p = 0.58$ ] and side ("left side versus right side" and "lower lip versus upper lip") [ $F(1, 8) = 0.18, p = 0.68$ ] were not significant. The group-by-side interaction approached significance [ $F(1, 8) = 4.63, p = 0.063$ ] (see Figure 3). A follow-up Mann-Whitney U test was conducted for the lower lip quadrants for a number of reasons. First, there was clearly lack of homogeneity in terms of the variance across conditions (Table 3). Secondly, several studies have suggested that the upper and lower lips were organized in non-overlapping quadrants under distinct neural control even during coordinated events and greater activity was displayed by the lower lip quadrants in comparison to the upper lip quadrants (Abbs, & Gracco, 1984; Goffman & Smith, 1994; Gracco & Abbs, 1985; McClean, 1996; Wohlert & Goffman, 1994). Further, electrodes attached to the lower lips have been reported to record more continuous muscle activity than electrodes attached to the upper lips (Wohlert & Hammen, 2000). To look specifically at laterality differences,

Table 3. Peak electromyographic (EMG) values in microvolts ( $\mu$ V) for the group of adults who stutter (AWS) and group of adults who do not stutter (AWNS) recorded during /f/-word productions for the left upper (LU) lip, right upper (RU) lip, left lower (LL) lip, and right lower (RL) lip.

Peak amplitude ( $\mu$ V) for /f/-word production									
AWS Participant	LU	RU	LL	RL	AWNS Participant	LU	RU	LL	RL
1	6.79	43.28	11.28	8.29	1	4.80	5.66	6.63	21.73
2	29.31	4.41*	27.88	18.58	2	209.55	294.61	82.34	484.88**
3	83.58	28.07	297.65**	17.12	3	6.33	4.68*	13.19	101.67
4	15.05	30.41	39.19	6.94	4	6.96	5.17	4.17	7.15
5	11.06	9.16	20.79	5.20	5	10.71	5.78	9.58	40.92
<b>Group mean</b>	<b>29.16</b>	<b>23.07</b>	<b>79.36</b>	<b>11.23</b>	<b>Group mean</b>	<b>47.67</b>	<b>63.18</b>	<b>23.18</b>	<b>131.27</b>
<b>Group SD</b>	<b>28.24</b>	<b>14.35</b>	<b>109.5</b>	<b>5.52</b>	<b>Group SD</b>	<b>80.96</b>	<b>115.72</b>	<b>29.73</b>	<b>179.71</b>

\* lowest peak amplitude

\*\* highest peak amplitude

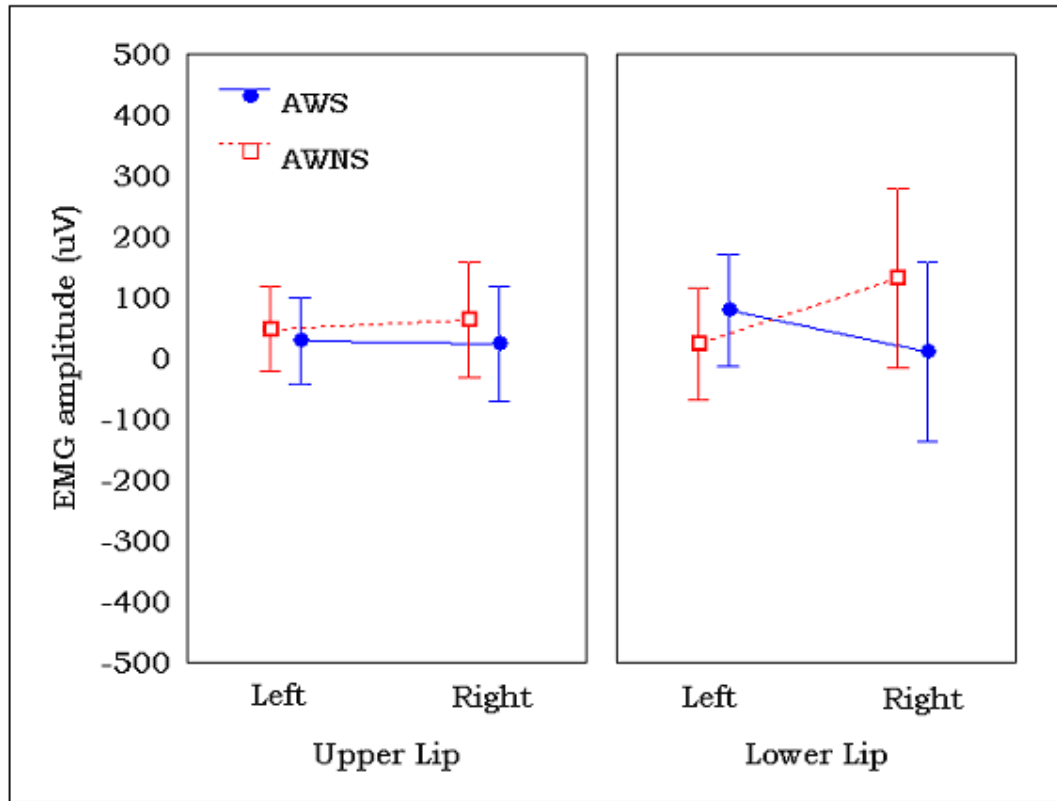


Figure 3. Depiction of result of a three-way repeated-measures ANOVA analysis for EMG amplitude for /f/-word production. The result of the 2 x 2 x 2 (AWS versus AWNS; left upper lip versus right upper lip; left lower lip versus right lower lip) ANOVA for group-by-side interaction approached significance ( $p=0.06$ ). The vertical bars denote 0.95 confidence intervals.

the non-parametric Mann-Whitney U test was therefore conducted separately for EMG measures for the upper lips and then for the lower lips, in each case using a “difference score” between left EMG and right EMG for each participant and then comparing those difference scores across the two groups. Results of the Mann-Whitney U test revealed a significant difference in the lower lips between the LL and RL quadrants for the AWS and AWNS groups [ $U(n_1=5, n_2=5)=0, p=0.004$ ]. No significant difference was found in the upper lips between the LU and RU quadrants [ $U(n_1=5, n_2=5)=9, p=0.23$ ]. The difference score between the left EMG and right EMG for the upper and lower lips are depicted in Figure 4.

The peak amplitudes obtained for all participants for each lip location are depicted graphically in Figure 5 for the AWS and Figure 6 for the AWNS. The four lip sites were ranked in order of highest peak EMG activity. For the AWS group, three of the participants (AWS 3-5) displayed the highest amplitude at the LL quadrant and the lowest at the RL quadrant. One participant (AWS 1) displayed the highest amplitude at the RU quadrant and the lowest amplitude at the LU quadrant. The remaining participant (AWS 2) displayed the highest and lowest amplitude at the LU and RU quadrants, respectively. The group mean amplitude for AWS was highest at the LL quadrant and lowest at the RL quadrant. Among the AWNS, all participants displayed the highest amplitude at the RL quadrant. Two AWNS participants (AWNS 2 & 4) displayed the lowest peak amplitude at the LL, while another two participants (AWNS 3 & 5) displayed the lowest peak amplitude at the RU quadrant. Only one participant (AWNS 1) displayed the lowest peak amplitude at the LU quadrant. The group mean amplitude for AWNS was highest at the RL quadrant and lowest at the LL quadrant.

In order to determine whether the EMG values of the various lip locations were correlated, a series of Pearson Product-Moment Correlation coefficients were calculated

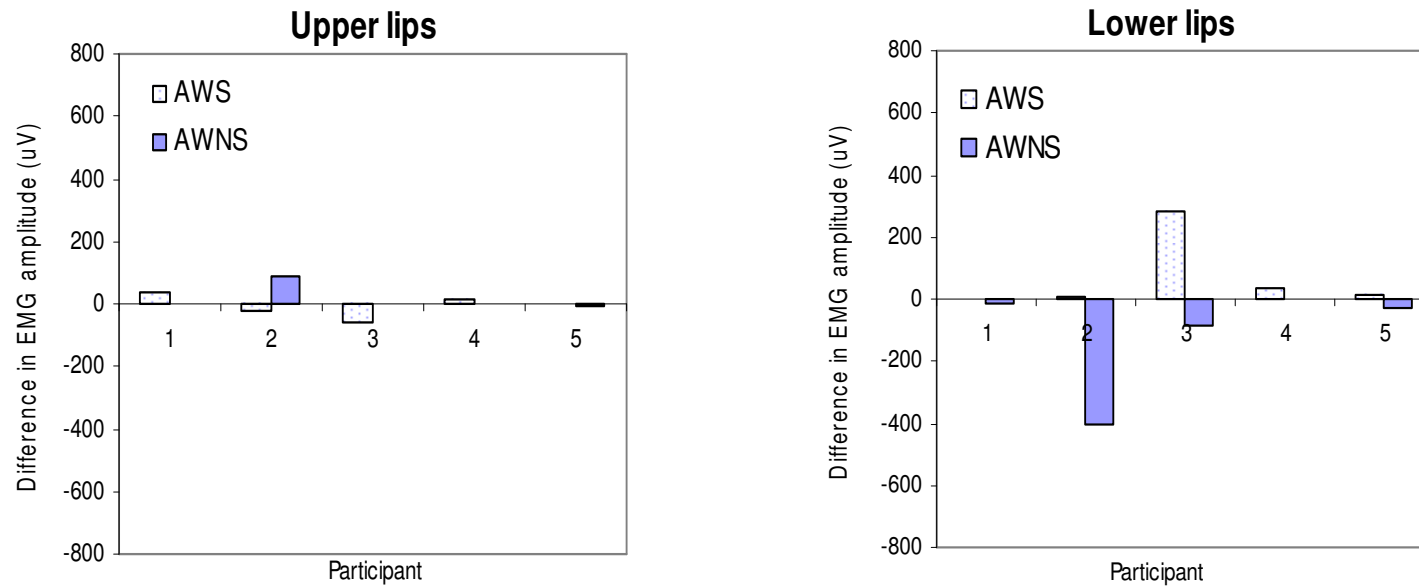


Figure 4. Histograms of the difference score for /f/-word production for the upper and lower lips for adults who stutter (AWS) and adults who do not stutter (AWNS). The difference score for the upper lip was derived from the difference in EMG amplitude between the left upper (LU) and right upper (RU) lip quadrants. The difference score for the lower lips was derived from the difference in EMG amplitude between the left lower (LL) and right lower (RL) lip quadrants. Each pair of AWS and AWNS participant was sex- and age-matched.



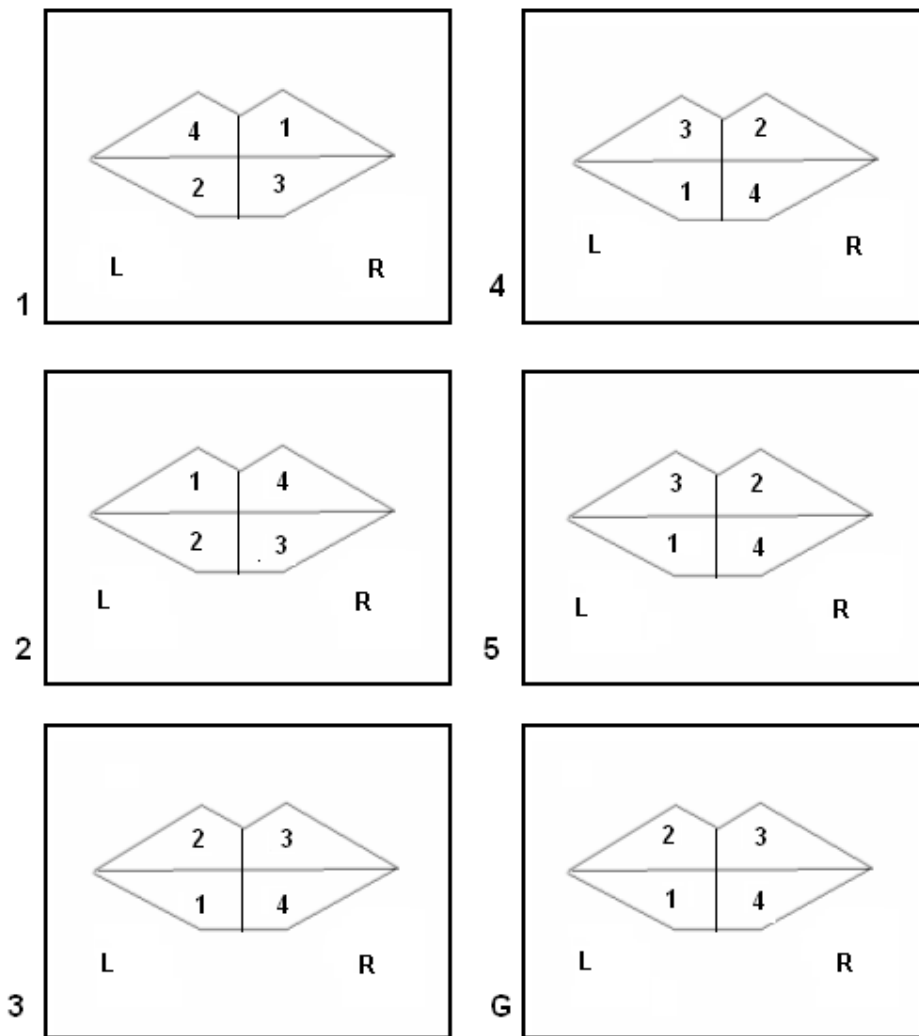


Figure 5. Depiction of peak electromyographic (EMG) amplitudes for the group of adults who stutter (AWS) recorded in the four quadrants of the lips for /f/-word production. The quadrant with the highest peak amplitude is labeled '1' while the quadrant with the lowest peak amplitude is designated as '4'. Panel 1 and 2 reflect the peak amplitudes for participants 1 and 2, respectively. Panel 3, 4 and 5 reflect the peak amplitudes for participants 3, 4, and 5, respectively. Panel G reflects the mean amplitude for the AWS group.

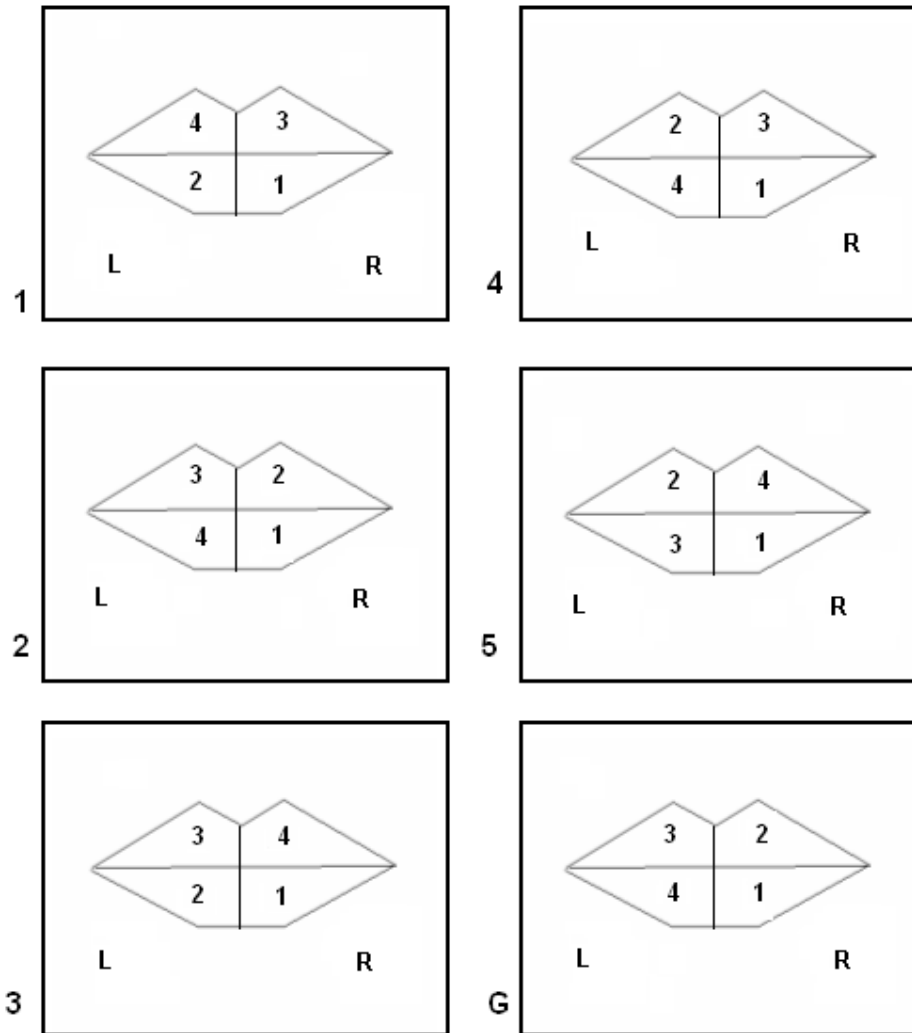


Figure 6. Depiction of peak amplitudes for the group of adults who do not stutter (AWNS) recorded in the four quadrants of the lips for /f/-word production. The quadrant with the highest peak amplitude is labeled '1' while the quadrant with the lowest peak amplitude is designated as '4'. Panel 1 and 2 reflect the peak amplitudes for participants 1 and 2, respectively. Panel 3, 4 and 5 reflect the peak amplitudes for participants 3, 4, and 5, respectively. Panel G reflects the mean amplitude for the AWNS group.

for each group. The results of the various correlations for the AWS and AWNS groups are shown in Table 4. Among the AWS group, only one correlation for LU-LL ( $r=0.97$ ,  $p < 0.05$ ) was significant, indicating that when the peak amplitude of LU was high, so too was the amplitude of the LL site. The other lip pairings were not significantly correlated including LU-RU ( $r= -0.017$ ,  $p=0.978$ ), LU-RL ( $r=0.71$ ,  $p=0.17$ ), LL-RL ( $r=0.54$ ,  $p=0.34$ ), RU-RL ( $r= -0.290$ ,  $p=0.63$ ) and RU-LL ( $r=0.15$ ,  $p=0.80$ ). A graphic representation of the only significant correlation is shown in Figure 7. None of the remaining lip positions were correlated in regard to peak EMG amplitude. For the AWNS group, all possible lip comparisons were correlated ( $r \geq 0.98$ ,  $p < 0.05$ ). A graphic representation of the correlation is shown in Figure 8.

*Single /p/-word production.* The results for the peak EMG amplitude of /p/-word production are listed on Table 5. There was considerable variability in peak amplitude between individuals within each group. Within the AWS group, individual peak amplitudes ranged from 5.32  $\mu$ V (AWS 2) to 182.09  $\mu$ V (AWS 3). For AWNS, individual peak amplitudes ranged from 4.84  $\mu$ V (AWNS 3) to 236.60  $\mu$ V (AWNS 2). For the AWS group mean amplitude, the peak EMG values across the four lip locations ranged from 11.51 $\mu$ V (RL) to 58.22  $\mu$ V (LL). For the AWNS group mean amplitude, the peak EMG values ranged from 21.85  $\mu$ V (LL) to 71.43  $\mu$ V (RL). In order to evaluate whether the peak EMG amplitudes at the lip locations differed between the two speaking groups, a 2 x 2 x 2 (AWS versus AWNS; left upper lip versus right upper lip; left lower lip versus right lower lip) ANOVA was performed. The main effect of group (AWS versus AWNS) [ $F(1, 8)= 0.48$ ,  $p= 0.83$ ] and side ("left side versus right side" and "lower lip versus upper lip") [ $F(1, 8) = 0.002$ ,  $p=0.96$ ] were not significant. In contrast, the group-by-side interaction was significant [ $F(1, 8) = 6.19$ ,  $p = 0.037$ ] (see Figure 9). A follow-up Mann-Whitney U test was conducted for the upper and lower lip quadrants for a number of reasons. First, there

Table 4. Correlation matrix for the adults who stutter (AWS) and adults who do not stutter (AWNS) for /f/-word production. Correlations were calculated for the four lip quadrants: left upper (LU), right upper (RU), left lower (LL) and right lower (RL). Correlations in boldface were significant at the  $p<0.05$  level.

AWS				
LU	1.0			
RU	-0.017	1.0		
LL	<b>0.971</b>	0.152	1.0	
RL	0.715	-0.290	0.541	1.0
	LU	RU	LL	RL

AWNS				
LU	1.0			
RU	<b>1.000</b>	1.0		
LL	<b>0.995</b>	<b>0.995</b>	1.0	
RL	<b>0.984</b>	<b>0.983</b>	<b>0.996</b>	1.0
	LU	RU	LL	RL

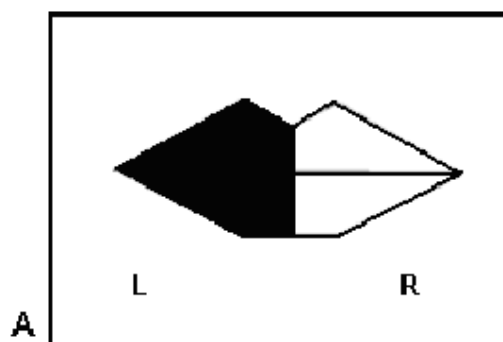


Figure 7. Depiction of the significant correlation for the left upper and left lower (LU-LL) lip pairing ( $r = 0.97$ ,  $p < 0.05$ ) for the group of adults who stutter (AWS) for /f/-word production.

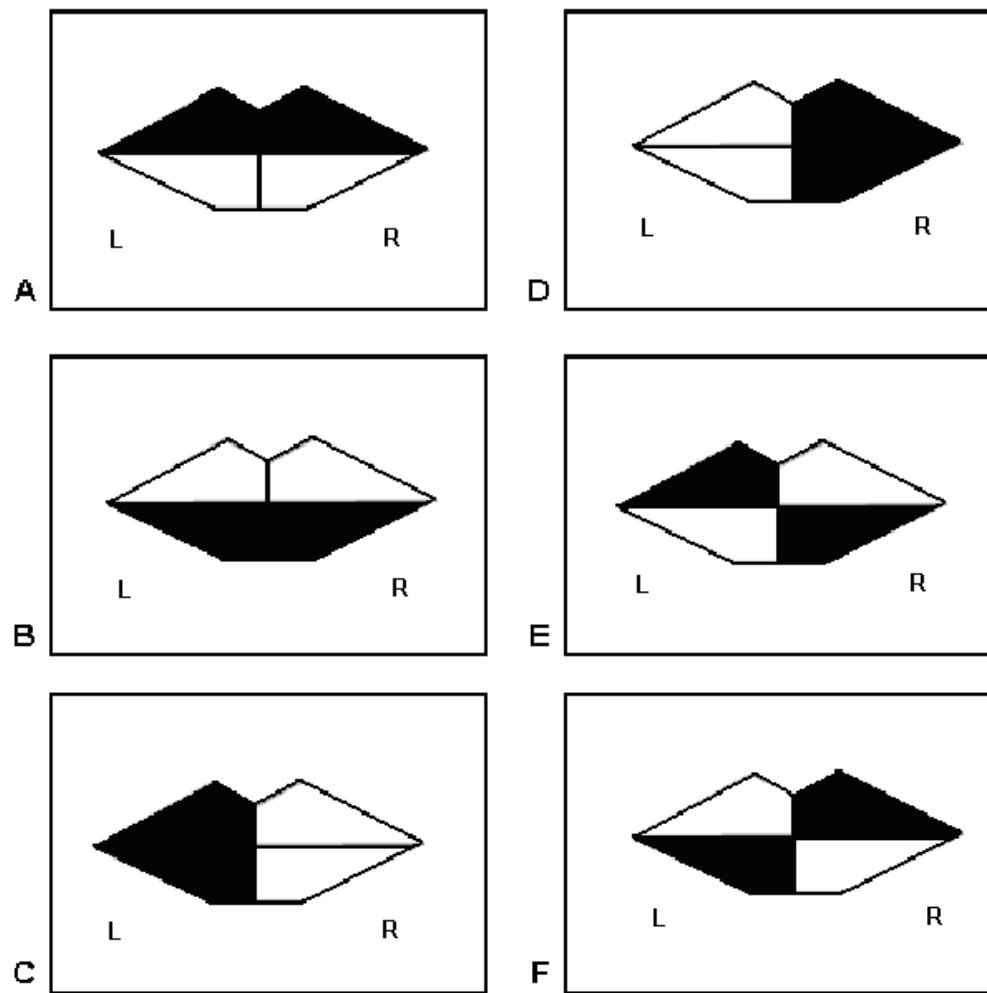


Figure 8. Depiction of significant correlation coefficients for lip quadrants for the group of adults who do not stutter (AWNS) for /f/-word production. Panel A, B, C and D reflect correlations for the ipsilateral pairings of left upper and right upper (LU-RU) lips ( $r=1.00$ ,  $p < 0.0001$ ), left lower and right lower (LL-RL) lips ( $r=0.99$ ,  $p < 0.001$ ), left upper and left lower (LU-LL) lips ( $r = 0.99$ ,  $p < 0.001$ ) and right upper and right lower (RU-RL) lips ( $r = 0.98$ ,  $p < 0.05$ ), respectively. Panels E and F reflect correlations for the diagonal pairings of left upper and right lower (LU-RL) lips ( $r = 0.98$ ,  $p < 0.05$ ) and right upper and left lower (RU-LL) lips ( $r = 0.99$ ,  $p < 0.001$ ), respectively.

Table 5. Peak electromyographic (EMG) values in microvolts ( $\mu$ V) for the group of adults who stutter (AWS) and group of adults who do not stutter (AWNS) recorded during /p/-word productions for the left upper (LU) lip, right upper (RU) lip, left lower (LL) lip, and right lower (RL) lip.

Peak amplitude ( $\mu$ V) for /p/-word production									
AWS Participant	LU	RU	LL	RL	AWNS Participant	LU	RU	LL	RL
1	8.13	38.86	12.73	13.53	1	5.54	6.03	13.74	26.29
2	14.96	5.32*	37.48	14.09	2	175.94	134.68	64.52	236.60**
3	90.30	51.53	182.09**	15.05	3	5.84	4.84*	9.40	42.93
4	21.03	109.84	38.08	9.46	4	13.43	14.53	11.35	11.24
5	17.04	11.71	20.70	5.41	5	12.32	12.43	10.25	40.07
<b>Group mean</b>	<b>30.29</b>	<b>43.45</b>	<b>58.22</b>	<b>11.51</b>	<b>Group mean</b>	<b>42.61</b>	<b>34.50</b>	<b>21.85</b>	<b>71.43</b>
<b>Group SD</b>	<b>30.29</b>	<b>37.30</b>	<b>62.70</b>	<b>3.60</b>	<b>Group SD</b>	<b>66.74</b>	<b>50.22</b>	<b>83.35</b>	<b>21.38</b>

\* lowest peak amplitude

\*\* highest peak amplitude

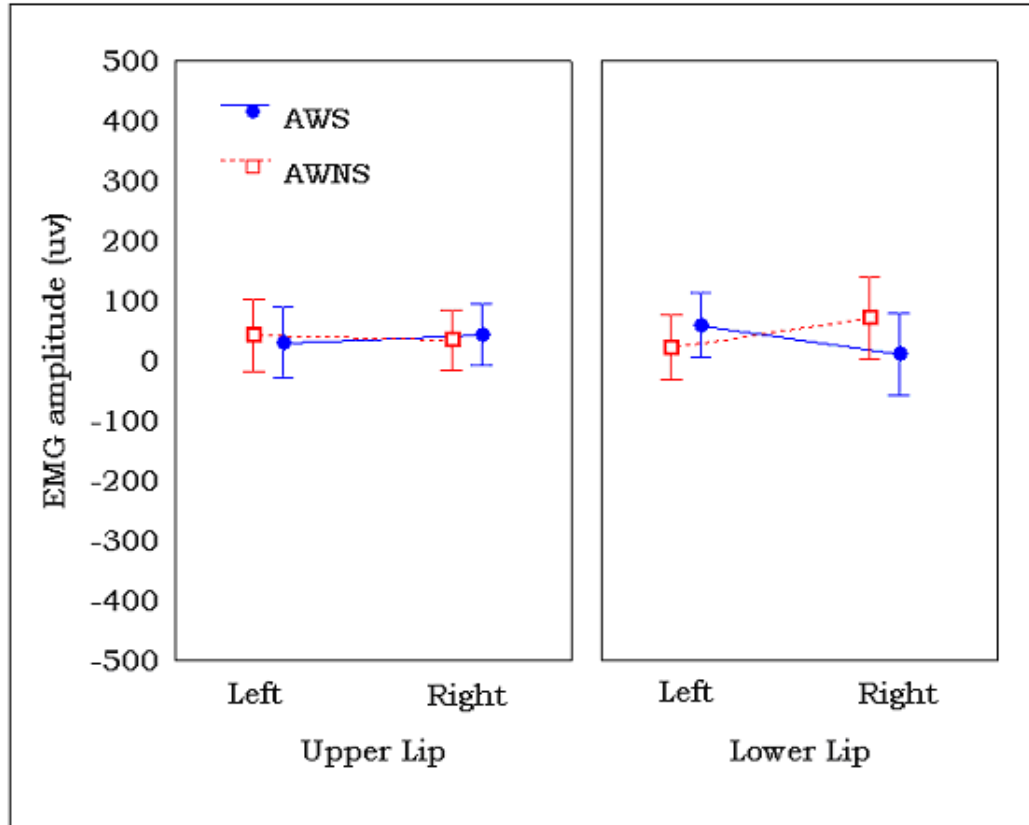


Figure 9. Depiction of result of a three-way repeated-measures ANOVA analysis for EMG amplitude for /p/-word production. The result of the 2 x 2 x 2 (AWS versus AWNS; left upper lip versus right upper lip; left lower lip versus right lower lip) ANOVA for group-by-side interaction was significant [ $F(1, 8) = 6.19$ ,  $p = 0.037$ ]. The vertical bars denote 0.95 confidence intervals.



was clearly a lack of homogeneity in terms of the variance across conditions (Table 5). Secondly, several studies have suggested that the upper and lower lips are organized in non-overlapping quadrants under distinct neural control, even during coordinated events and greater activity was displayed by the lower lip quadrants in comparison to the upper lip quadrants (Abbs, & Gracco, 1984; Goffman & Smith, 1994; Gracco & Abbs, 1985; McClean, 1996; Wohlert & Goffman, 1994). Further, electrodes attached to the lower lips have been reported to record more continuous muscle activity than electrodes attached to the upper lips (Wohlert & Hammen, 2000). To look specifically at laterality differences, the non-parametric Mann-Whitney U test was therefore conducted separately for EMG measures for the upper lips and then for the lower lips, in each case using a “difference score” between left EMG and right EMG for each participant and then comparing those difference scores across the two groups. Results of the Mann-Whitney U test confirmed differences in the lower lips between the LL and RL quadrants for the AWS and AWNS groups [ $U(n_1=5, n_2=5)=1, p=0.008$ ]. No significant difference was found in the upper lips between the LU and RU quadrants [ $U(n_1=5, n_2=5)=12, p=0.45$ ]. The difference score between the left EMG and right EMG for the upper and lower lips are depicted in Figure 10.

The peak amplitudes obtained for each lip location are depicted in Figure 11 for the AWS participants and Figure 12 for AWNS participants. The four lip sites were ranked in order of highest peak EMG activity. For the AWS group, two participants (AWS 1 & 4) displayed the highest amplitude at the RU quadrant and the lowest amplitude at either the LU quadrant (AWS 1) or RL quadrant (AWS 4). The three remaining participants (AWS 2, 3 & 5) displayed the highest amplitude at the LL quadrant and the lowest amplitude at either the RU quadrant (AWS 2) or RL quadrant (AWS 3 & 5). The group mean amplitude for AWS was highest at the LL quadrant and lowest at the RL quadrant. Among the

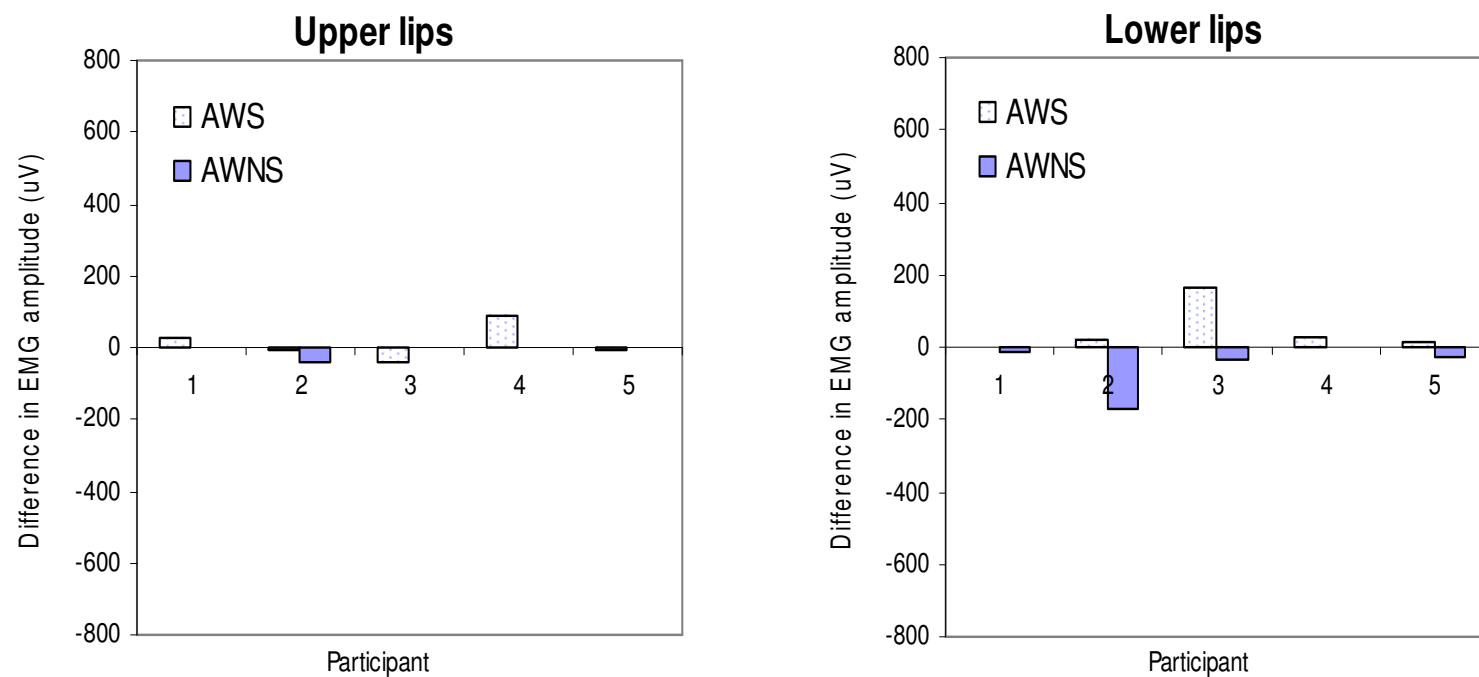


Figure 10. Histograms of the difference score for /p/-word production for the upper and lower lips for adults who stutter (AWS) and adults who do not stutter (AWNS). The difference score for the upper lip was derived from the difference in EMG amplitude between the left upper (LU) and right upper (RU) lip quadrants. The difference score for the lower lips was derived from the difference in EMG amplitude between the left lower (LL) and right lower (RL) lip quadrants. Each pair of AWS and AWNS participant was sex- and age-matched.

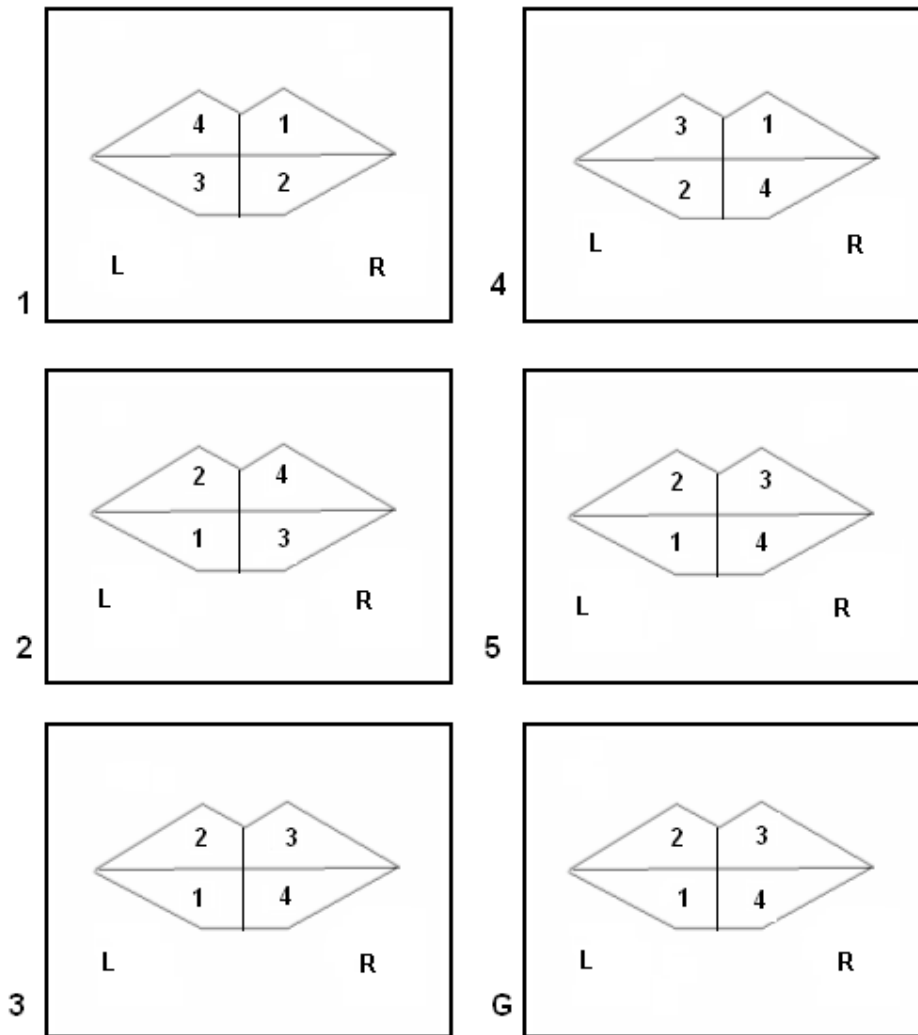


Figure 11. Diagram of peak amplitudes for the group of adults who stutter (AWS) recorded in the four quadrants of the lips for /p/-word production. The quadrant with the highest peak amplitude is labeled '1' while the quadrant with the lowest peak amplitude is designated as '4'. Panel 1 and 2 reflect the peak amplitudes for participants 1 and 2, respectively. Panel 3, 4 and 5 reflect the peak amplitudes for participants 3, 4, and 5, respectively. Panel G reflects the mean amplitude for the AWS group.

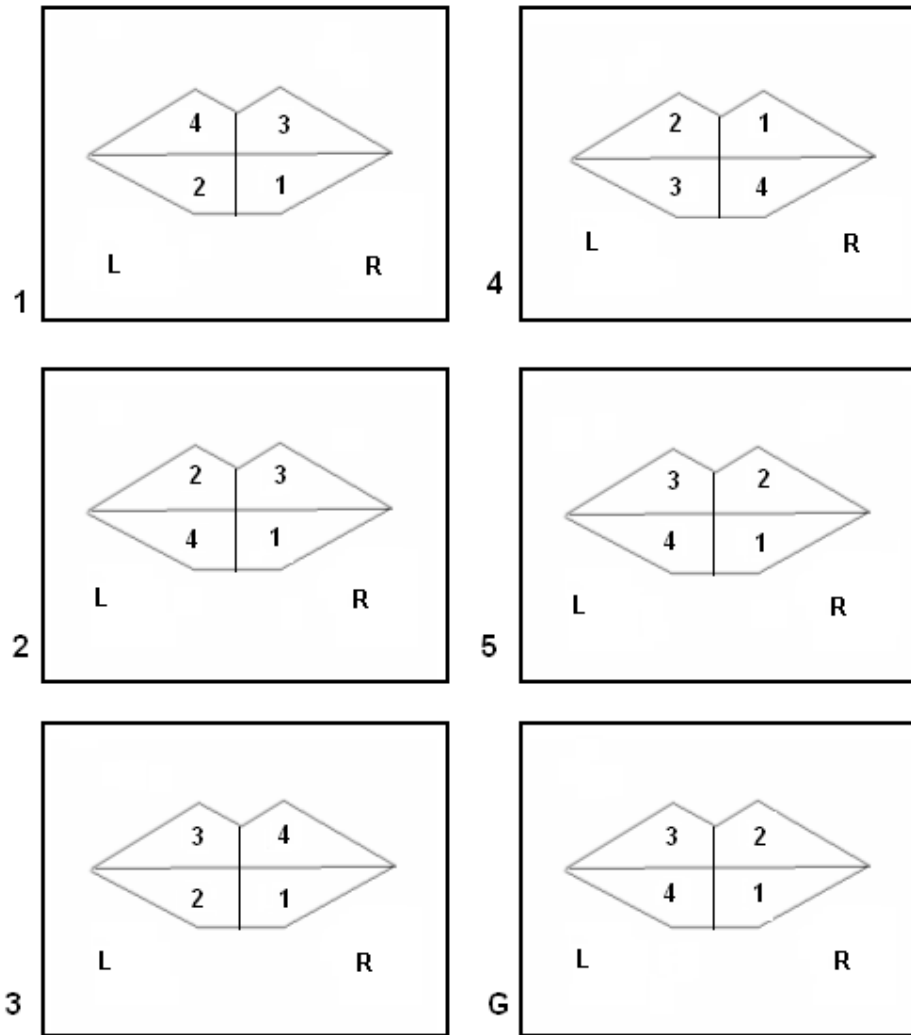


Figure 12. Diagram of peak amplitudes for the group of adults who do not stutter (AWNS) recorded in the four quadrants of the lips for /p/-word production. The quadrant with the highest peak amplitude is labeled '1' while the quadrant with the lowest peak amplitude is designated as '4'. Panel 1 and 2 reflect the peak amplitudes for participants 1 and 2, respectively. Panel 3, 4 and 5 reflect the peak amplitudes for participants 3, 4, and 5, respectively. Panel G reflects the mean amplitude for the AWNS group.

AWNS, four participants (AWNS 1-3 & 5) displayed the highest amplitude at the RL quadrant and the lowest amplitude at either the LU quadrant (AWNS 1), LL quadrant (AWNS 2 & 5) or RL quadrant (AWNS 3). Only one participant (AWNS 4) displayed the highest and lowest amplitude at the RU and RL quadrants, respectively. The group mean amplitude for AWNS was highest at the RL quadrant and lowest at the LL quadrant.

In order to determine whether the EMG values of the various lip locations were correlated, a series of Pearson Product-Moment Correlation coefficients were calculated for each group. The results of the various correlations for the AWS and AWNS groups are shown in Table 6. Among the AWS group, only one correlation for LU-LL was significant ( $r = 0.99, p < 0.001$ ), indicating that when the peak amplitude of LU was high, so too was the amplitude of the LL site. The other lip pairings were not significantly correlated including LU-RU ( $r = 0.17, p = 0.78$ ), LL-RL ( $r = 0.50, p = 0.39$ ), RU-RL ( $r = -0.032, p = 0.95$ ), LU-RL ( $r = 0.41, p = 0.48$ ) and RU-LL ( $r = 0.15, p = 0.79$ ). A visual representation of the only significant correlation is shown in Figure 13. For the AWNS group, all possible lip comparisons were correlated ( $r \geq 0.98, p < 0.05$ ). A graphic representation of the correlation is shown in Figure 14.

*Single-sentence reading.* The results for the peak EMG amplitude of sentence production are listed on Table 7. Considerable variability in peak amplitude was displayed by both AWS and AWNS groups. Within the AWS group, individual peak amplitudes ranged from 7.00  $\mu\text{V}$  (AWS 2) to 500.41  $\mu\text{V}$  (AWS 3). For AWNS, individual peak amplitudes ranged from 6.47  $\mu\text{V}$  (AWNS 3) to 663.28  $\mu\text{V}$  (AWNS 2). For the AWS group mean amplitude, the peak EMG values across the four lip locations ranged from 16.22  $\mu\text{V}$  (RL) to 122.77  $\mu\text{V}$  (LL). For the AWNS group, the mean peak EMG values ranged from 63.65  $\mu\text{V}$  (LL) to 166.93  $\mu\text{V}$  (RL). In order to evaluate whether the peak EMG amplitudes at the lip locations differed between the two speaking groups, a 2 x 2 x 2 (AWS versus

Table 6. Correlation matrix for the adults who stutter (AWS) and adults who do not stutter (AWNS) for /p/-word production. Correlations were calculated for the four lip quadrants: left upper (LU), right upper (RU), left lower (LL) and right lower (RL). Correlations in boldface were significant at the  $p<0.05$  level.

AWS					AWNS				
LU	1.0				LU	1.0			
RU	0.173	1.0			RU	<b>1.000</b>	1.0		
LL	<b>0.994</b>	0.159	1.0		LL	<b>0.996</b>	<b>0.995</b>	1.0	
RL	0.418	-0.032	0.500	1.0	RL	<b>0.987</b>	<b>0.983</b>	<b>0.983</b>	1.0
	LU	RU	LL	RL		LU	RU	LL	RL

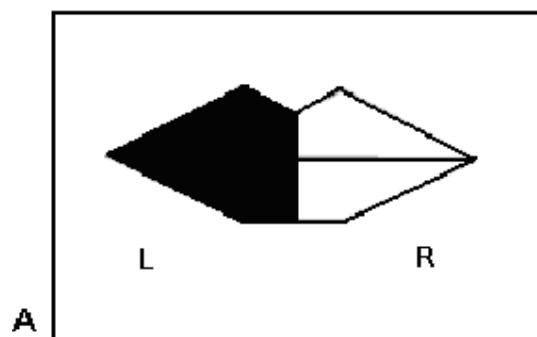


Figure 13. Depiction of significant correlation ( $r = 0.99$ ,  $p < 0.001$ ) for the left upper and left lower (LU-LL) lip pairing for the group of adults who stutter (AWS) for /p/-word production.

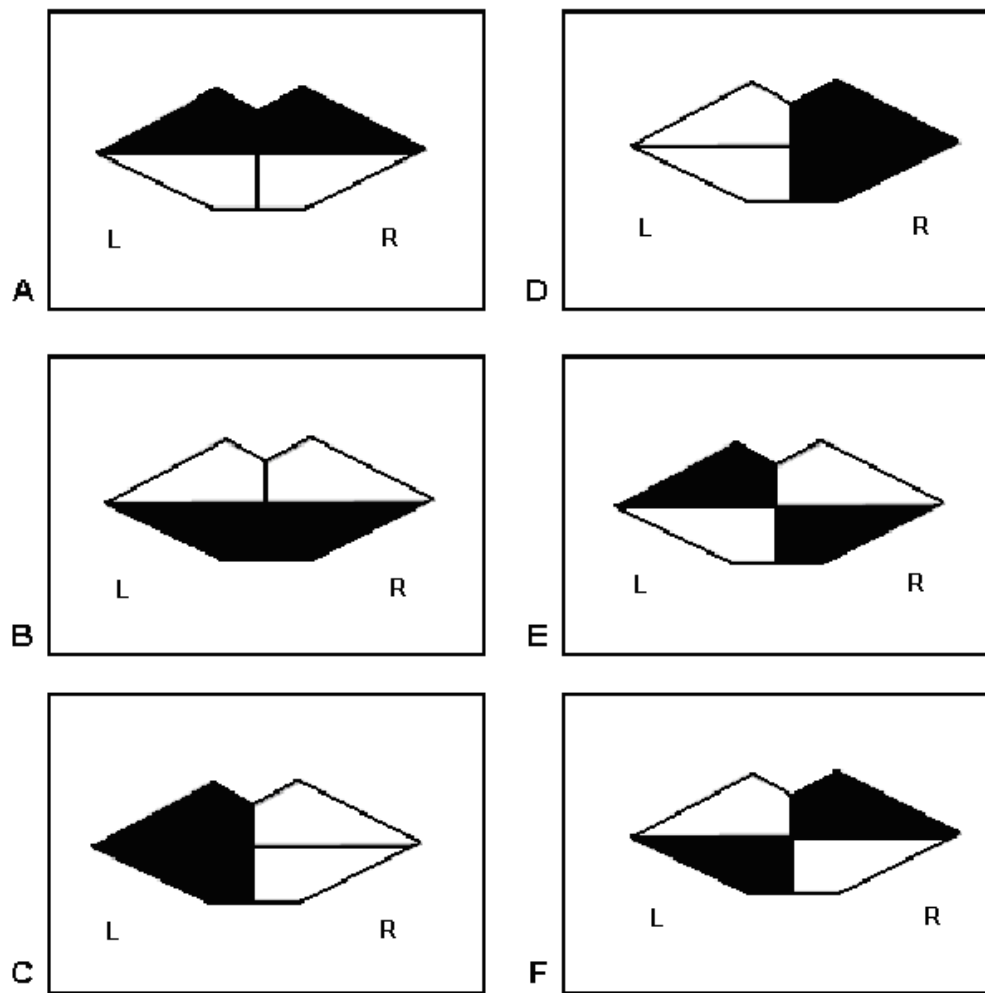


Figure 14. Depiction of significant correlation coefficients for lip quadrants for the group of adults who do not stutter (AWNS) for /p/-word production. Panel A, B, C and D reflect correlations for the ipsilateral pairings of left upper and right upper (LU-RU) lips ( $r = 1.00$ ,  $p < 0.0001$ ), left lower and right lower (LL-RL) lips ( $r = 0.98$ ,  $p < 0.05$ ), left upper and left lower (LU-LL) lips ( $r = 0.99$ ,  $p < 0.001$ ) and right upper and right lower (RU-RL) lips ( $r = 0.98$ ,  $p < 0.05$ ), respectively. Panels E and F reflect correlations for the diagonal pairings of left upper and right lower (LU-RL) lips ( $r = 0.98$ ,  $p < 0.05$ ) and right upper and left lower (RU-LL) lips ( $r = 0.99$ ,  $p < 0.001$ ), respectively.



Table 7. Peak electromyographic (EMG) values in microvolts ( $\mu$ V) for the group of adults who stutter (AWS) and group of adults who do not stutter (AWNS) recorded during single-sentence production for the left upper (LU) lip, right upper (RU) lip, left lower (LL) lip, and right lower (RL) lip.

Peak amplitude ( $\mu$ V) for Single-sentence production									
AWS Participant	LU	RU	LL	RL	AWNS Participant	LU	RU	LL	RL
1	16.87	74.80	19.43	9.89	1	8.40	7.99	13.56	40.11
2	25.60	7.00*	34.80	24.65	2	304.94	302.55	264.20	663.28**
3	137.78	146.54	500.41**	28.73	3	6.62	6.47*	18.39	73.46
4	28.82	102.28	34.69	10.76	4	15.80	6.50	7.48	7.90
5	20.71	13.47	24.50	7.09	5	13.35	101.33	14.60	49.92
<b>Group mean</b>	<b>45.96</b>	<b>68.82</b>	<b>122.77</b>	<b>16.22</b>	<b>Group mean</b>	<b>69.82</b>	<b>84.97</b>	<b>63.65</b>	<b>166.93</b>
<b>Group SD</b>	<b>46.09</b>	<b>53.07</b>	<b>188.92</b>	<b>8.73</b>	<b>Group SD</b>	<b>117.61</b>	<b>114.76</b>	<b>100.34</b>	<b>249.06</b>

\* lowest peak amplitude

\*\* highest peak amplitude

AWNS; left upper lip versus right upper lip; left lower lip versus right lower lip) ANOVA was performed. The main effect of group (AWS versus AWNS) [ $F(1, 8) = 0.16, p = 0.69$ ] and side ("left side versus right side" and "lower lip versus upper lip") [ $F(1, 8) = 0.11, p = 0.74$ ] were not significant. The group-by-side interaction was also not significant [ $F(1, 8) = 3.26, p = 0.109$ ] (see Figure 15). A follow-up Mann-Whitney U test was conducted for the lower lip quadrants for a number of reasons. First, there was clearly lack of homogeneity in terms of the variance across conditions (Table 7). Secondly, several studies have suggested that the upper and lower lips were organized in non-overlapping quadrants under distinct neural control even during coordinated events and greater activity was displayed by the lower lip quadrants in comparison to the upper lip quadrants (Abbs, & Gracco, 1984; Goffman & Smith, 1994; Gracco & Abbs, 1985; McClean, 1996; Wohlert & Goffman, 1994). Further, electrodes attached to the lower lips have been reported to record more continuous muscle activity than electrodes attached to the upper lips (Wohlert & Hammen, 2000). To look specifically at laterality differences, the non-parametric Mann-Whitney U test was therefore conducted separately for EMG measures for the upper lips and then for the lower lips, in each case using a "difference score" between left EMG and right EMG for each participant and then comparing those difference scores across the two groups. Results of the Mann-Whitney U test revealed a significant difference in the lower lips between the LL and RL quadrants for the AWS and AWNS groups [ $U(n_1=5, n_2=5)=0, p=0.004$ ]. No significant difference was found in the upper lips between the LU and RU quadrants [ $U(n_1=5, n_2=5)=12, p=0.45$ ]. The difference score between the left EMG and right EMG for the upper and lower lips are depicted in Figure 16.

The peak amplitudes obtained for all participants for each lip location are depicted in Figure 17 for the AWS and Figure 18 for the AWNS. The four lip sites were ranked in order of EMG activity. For the AWS group, three of the participants (AWS 2, 3 & 5)

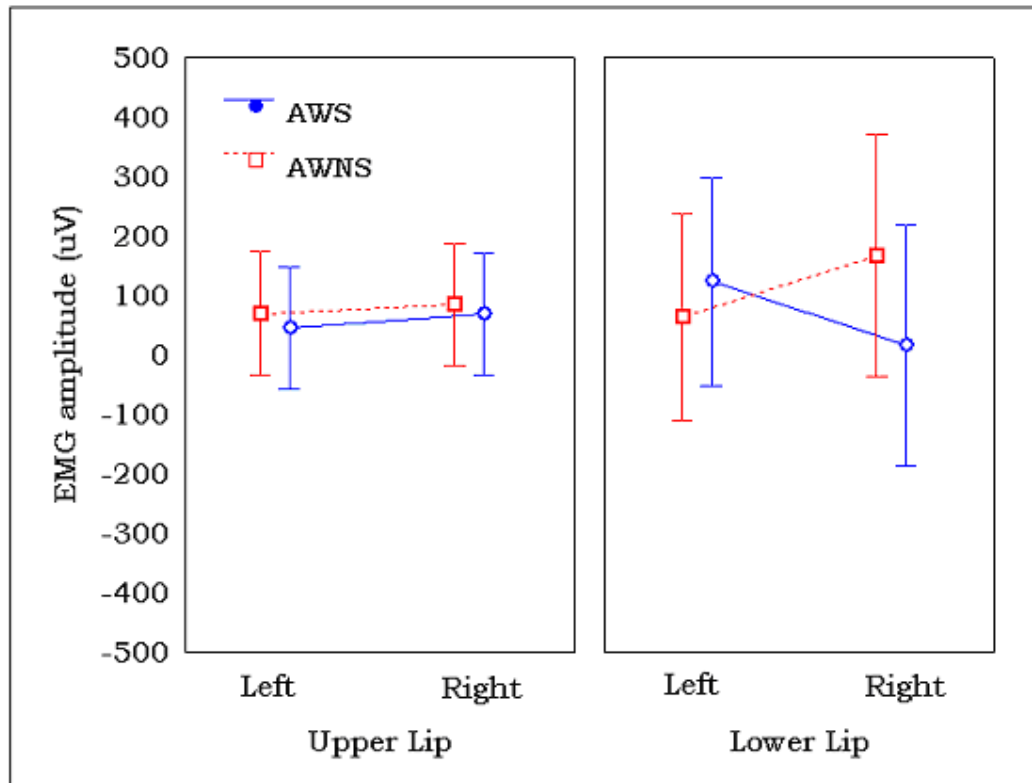


Figure 15. Depiction of result of a three-way repeated-measures ANOVA analysis for EMG amplitude for single-sentence production. The result of the 2 x 2 x 2 (AWS versus AWNS; left upper lip versus right upper lip; left lower lip versus right lower lip) ANOVA for group-by-side interaction was not significant [ $F(1, 8) = 3.26, p = 0.109$ ]. The vertical bars denote 0.95 confidence intervals.

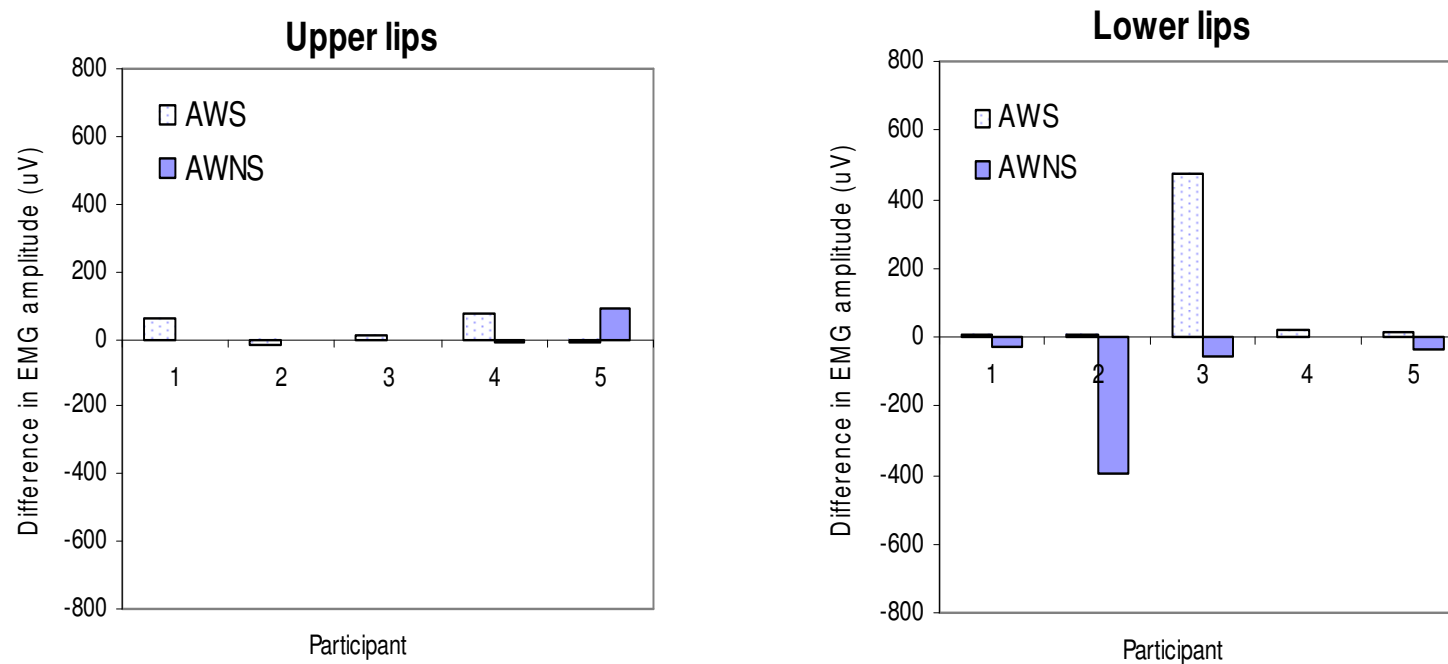


Figure 16. Histograms of the difference score for single-sentence reading for the upper and lower lips for adults who stutter (AWS) and adults who do not stutter (AWNS). The difference score for the upper lip was derived from the difference in EMG amplitude between the left upper (LU) and right upper (RU) lip quadrants. The difference score for the lower lips was derived from the difference in EMG amplitude between the left lower (LL) and right lower (RL) lip quadrants. Each pair of AWS and AWNS participant was sex- and age-matched.

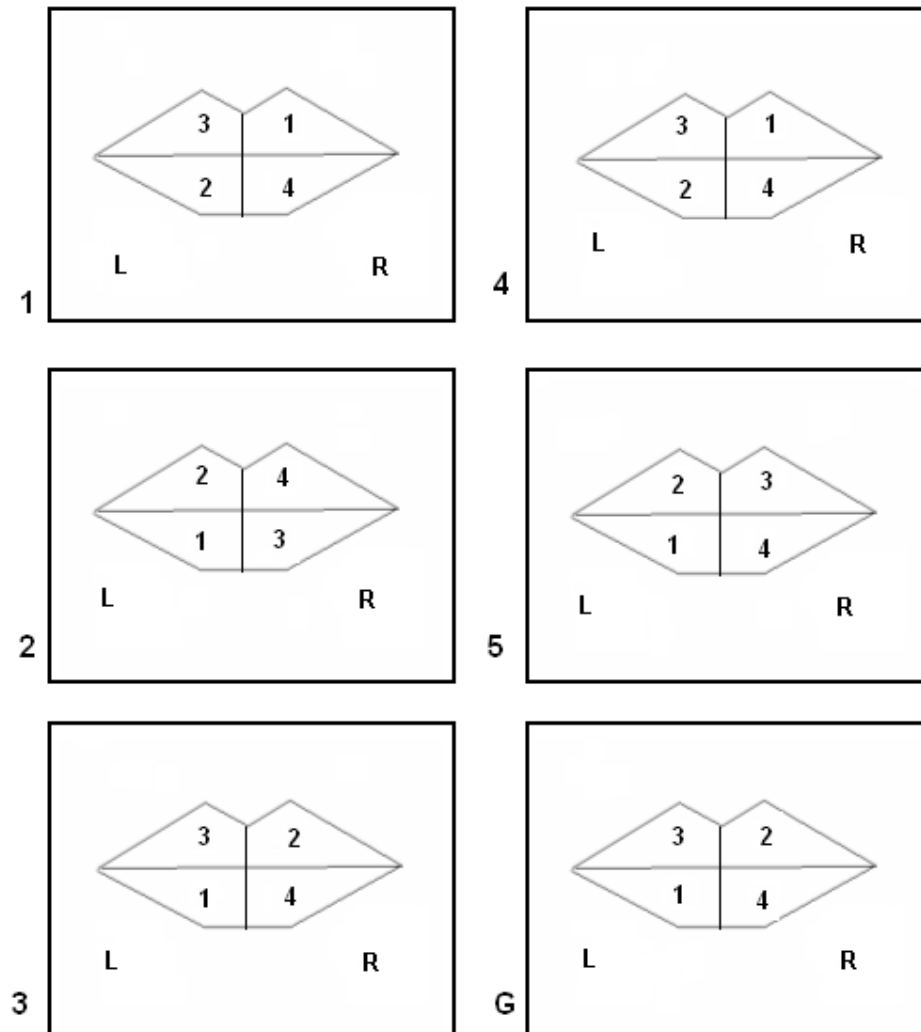


Figure 17. Diagram of peak amplitudes for the group of adults who do not stutter (AWS) recorded in the four quadrants of the lips for single-sentence production. The quadrant with the highest peak amplitude is labeled '1' while the quadrant with the lowest peak amplitude is designated as '4'. Panel 1 and 2 reflect the peak amplitudes for participants 1 and 2, respectively. Panel 3, 4 and 5 reflect the peak amplitudes for participants 3, 4, and 5, respectively. Panel G reflects the mean amplitude for the AWS group.

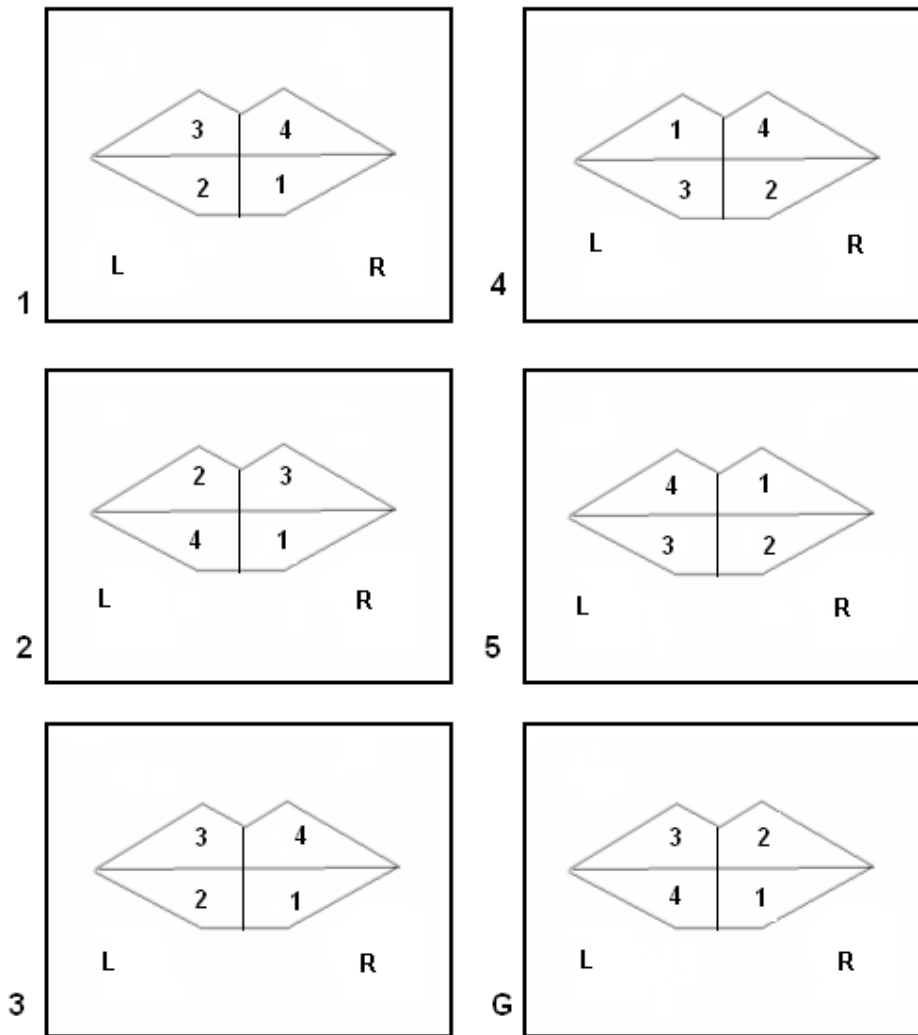


Figure 18. Diagram of peak amplitudes for the group of adults who do not stutter (AWNS) recorded in the four quadrants of the lips for single-sentence production. The quadrant with the highest peak amplitude is labeled '1' while the quadrant with the lowest peak amplitude is designated as '4'. Panel 1 and 2 reflect the peak amplitudes for participants 1 and 2, respectively. Panel 3, 4 and 5 reflect the peak amplitudes for participants 3, 4, and 5, respectively. Panel G reflects the mean amplitude for the AWS group.

displayed the highest amplitude at the LL quadrant and the lowest at either the RU (AWS 2) or RL (AWS 3 & 5) quadrant. The remaining two participants (AWS 1 & 4) displayed the highest amplitude at RU quadrant and the lowest amplitude at the RL quadrant. The group mean amplitude for AWS was highest and lowest at the LL and RL quadrants, respectively. Among the AWNS, three participants (AWNS 1-3) displayed the highest amplitude at the RL quadrant and the lowest amplitude at either the RU (AWNS 1 & 3) or LL (AWNS 2) quadrant. One participant (AWNS 4) displayed the highest amplitude at the LU quadrant and the lowest amplitude at the RU quadrant. The remaining participant (AWNS 5) displayed the highest amplitude at the RU quadrant and the lowest amplitude at the LU quadrant. The group mean amplitude for AWNS was highest and lowest at the RL and LL quadrants, respectively.

In order to determine whether the EMG values of the various lip locations were correlated, a series of Pearson Product-Moment Correlation coefficients were calculated for each group. The results of the various correlations for the AWS and AWNS groups are shown in Table 8. Among the AWS group, only one correlation LU-LL was significant ( $r=0.99$ ,  $p<0.0001$ ), indicating that when the peak amplitude of LU was high, so too was the amplitude of the LL site. The other lip pairings were not significantly correlated including LU-RU ( $r=0.74$ ,  $p=0.15$ ), LL-RL ( $r=0.73$ ,  $p=0.16$ ), RU-RL ( $r=0.31$ ,  $p=0.60$ ), LU-RL ( $r=0.73$ ,  $p=0.15$ ) and RU-LL ( $r=0.73$ ,  $p=0.16$ ). A visual representation of the only significant correlation is shown in Figure 19. For the AWNS group, all possible lip comparisons were correlated ( $r \geq 0.94$ ,  $p < 0.05$ ). A graphic representation of the correlation is shown in Figure 20.

Table 8. Correlation matrix for the adults who stutter (AWS) and adults who do not stutter (AWNS) for single-sentence production. Correlations were calculated for the four lip quadrants: left upper (LU), right upper (RU), left lower (LL) and right lower (RL). Correlations in boldface were significant at the  $p<0.05$  level.

AWS				
LU	1.0			
RU	0.740	1.0		
LL	<b>0.998</b>	0.731	1.0	
RL	0.738	0.318	0.730	1.0
	LU	RU	LL	RL

AWNS				
LU	1.0			
RU	<b>0.994</b>	1.0		
LL	<b>0.998</b>	<b>0.949</b>	1.0	
RL	<b>0.994</b>	<b>0.949</b>	<b>0.999</b>	1.0
	LU	RU	LL	RL



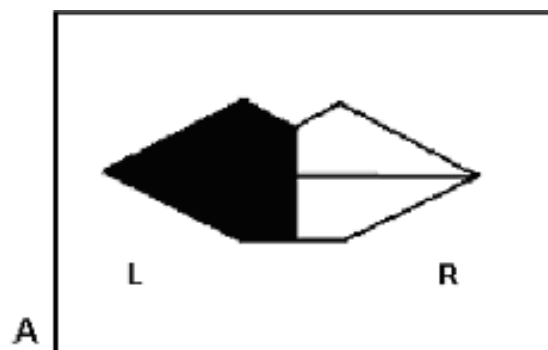


Figure 19. Depiction of significant correlation ( $r = 0.99$ ,  $p < 0.0001$ ) for the left upper and left lower (LU-LL) lip pairing for the group of adults who stutter (AWS) for single-sentence production.

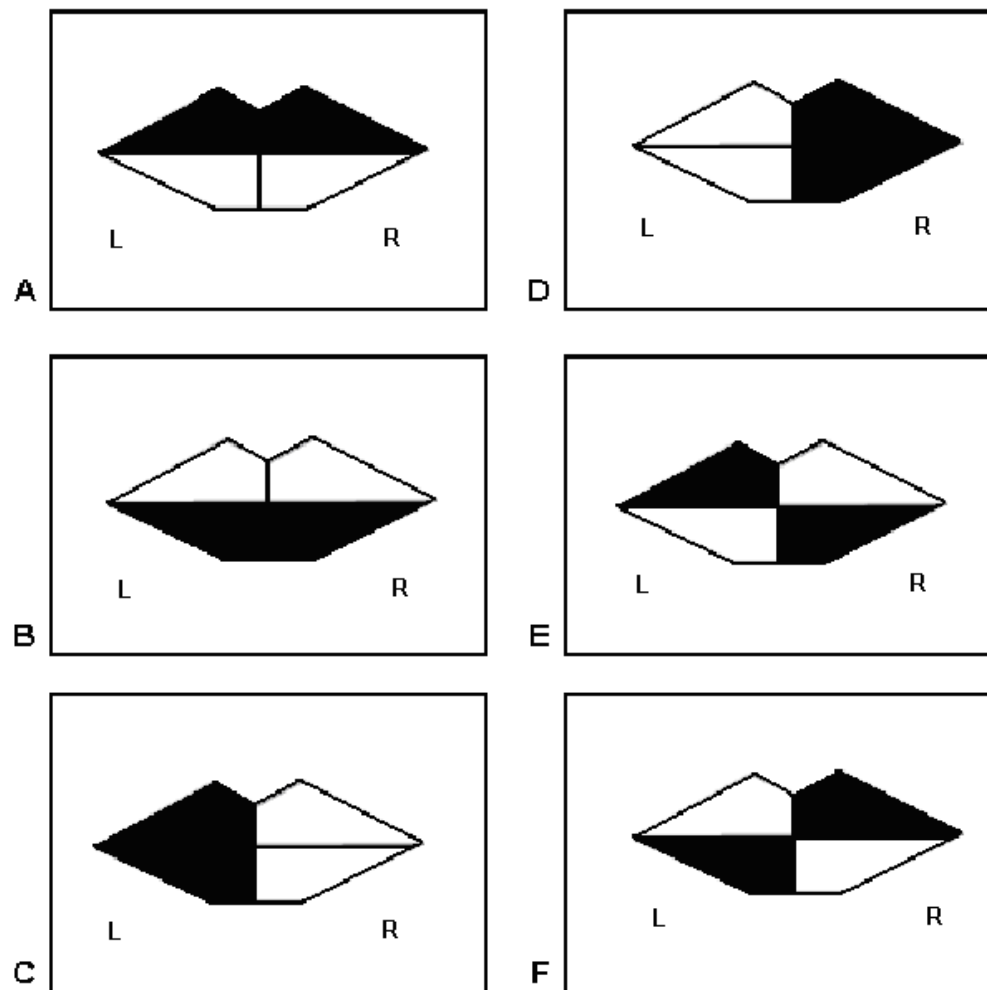


Figure 20. Depiction of significant correlation coefficients for lip quadrants for the group of adults who do not stutter (AWNS) for single-sentence production. Panel A, B, C and D reflect correlations for the ipsilateral pairings of left upper and right upper (LU-RU) lips ( $r = 0.95$ ,  $p < 0.05$ ), left lower and right lower (LL-RL) lips ( $r = 0.99$ ,  $p < 0.05$ ), left upper and left lower (LU-LL) lips ( $r = 0.99$ ,  $p < 0.0001$ ) and right upper and right lower (RU-RL) lips ( $r = 0.94$ ,  $p < 0.05$ ), respectively. Panels E and F reflect correlations for the diagonal pairings of left upper and right lower (LU-RL) lips ( $r = 0.99$ ,  $p < 0.001$ ), and right upper and left lower (RU-LL) lips ( $r = 0.94$ ,  $p < 0.05$ ), respectively.

### ***Non-speech Production Task***

*Lip pursing.* The results for the peak EMG amplitude for the non-speech production task are listed on Table 9. Considerable variability in peak amplitude was displayed by both AWS and AWNS groups. Individual peak amplitudes ranged from 3.95  $\mu$ V (AWS 2) to 847.13  $\mu$ V (AWS 3) for the AWS. For AWNS, individual peak amplitudes ranged from 3.34  $\mu$ V (AWNS 3) to 674.31  $\mu$ V (AWNS 2). For the AWS group mean amplitude, the peak EMG values across the four lip locations ranged from 23.72  $\mu$ V (RL) to 202.56  $\mu$ V (LL). For the AWNS group mean amplitude, the mean peak EMG values ranged from 21.98  $\mu$ V (LL) to 173.38  $\mu$ V (RL). In order to evaluate whether the peak EMG amplitudes at the lip locations differed between the two speaking groups, a 2 x 2 x 2 (AWS versus AWNS; left upper lip versus right upper lip; left lower lip versus right lower lip) ANOVA was performed. The main effect of group (AWS versus AWNS) [ $F(1, 8)=0.93, p=0.76$ ] and side ("left side versus right side" and "lower lip versus upper lip") [ $F(1, 8)=0.00, p=0.98$ ] were not significant. The group-by-side interaction approached significance [ $F(1, 8)=4.13, p=0.077$ ] (see Figure 21). A follow-up Mann-Whitney U test was conducted for the lower lip quadrants for a number of reasons. First, there was clearly lack of homogeneity in terms of the variance across conditions (Table 9). Secondly, several studies have suggested that the upper and lower lips were organized in non-overlapping quadrants under distinct neural control even during coordinated events and greater activity was displayed by the lower lip quadrants in comparison to the upper lip quadrants (Abbs, & Gracco, 1984; Goffman & Smith, 1994; Gracco & Abbs, 1985; McClean, 1996; Wohlert & Goffman, 1994). Further, electrodes attached to the lower lips have been reported to record more continuous muscle activity than electrodes attached to the upper lips (Wohlert & Hammen, 2000). To look specifically at laterality differences, the non-parametric Mann-Whitney U test was therefore conducted separately for EMG measures for the upper lips

Table 9. Peak electromyographic (EMG) values in microvolts ( $\mu$ V) for the group of adults who stutter (AWS) and group of adults who do not stutter (AWNS) recorded during lip pursing for the left upper (LU) lip, right upper (RU) lip, left lower (LL) lip, and right lower (RL) lip.

Peak amplitude ( $\mu$ V) for Lip Pursing									
AWS Participant	LU	RU	LL	RL	AWNS Participant	LU	RU	LL	RL
1	26.69	95.05	19.92	13.50	1	5.84	8.97	9.88	30.83
2	13.81	3.95*	32.05	14.48	2	132.52	143.96	77.29	674.31**
3	323.40	56.13	847.13**	61.68	3	11.30	9.24	9.72	55.28
4	32.05	93.76	76.65	12.84	4	13.05	6.59	3.34*	5.84
5	32.35	19.61	37.04	16.12	5	28.10	34.05	9.66	100.63
<b>Group mean</b>	<b>85.66</b>	<b>53.70</b>	<b>202.56</b>	<b>23.72</b>	<b>Group mean</b>	<b>38.16</b>	<b>40.56</b>	<b>21.98</b>	<b>173.38</b>
<b>Group SD</b>	<b>119.06</b>	<b>37.30</b>	<b>322.85</b>	<b>19.01</b>	<b>Group SD</b>	<b>47.75</b>	<b>52.66</b>	<b>27.77</b>	<b>252.41</b>

\* lowest peak amplitude

\*\* highest peak amplitude

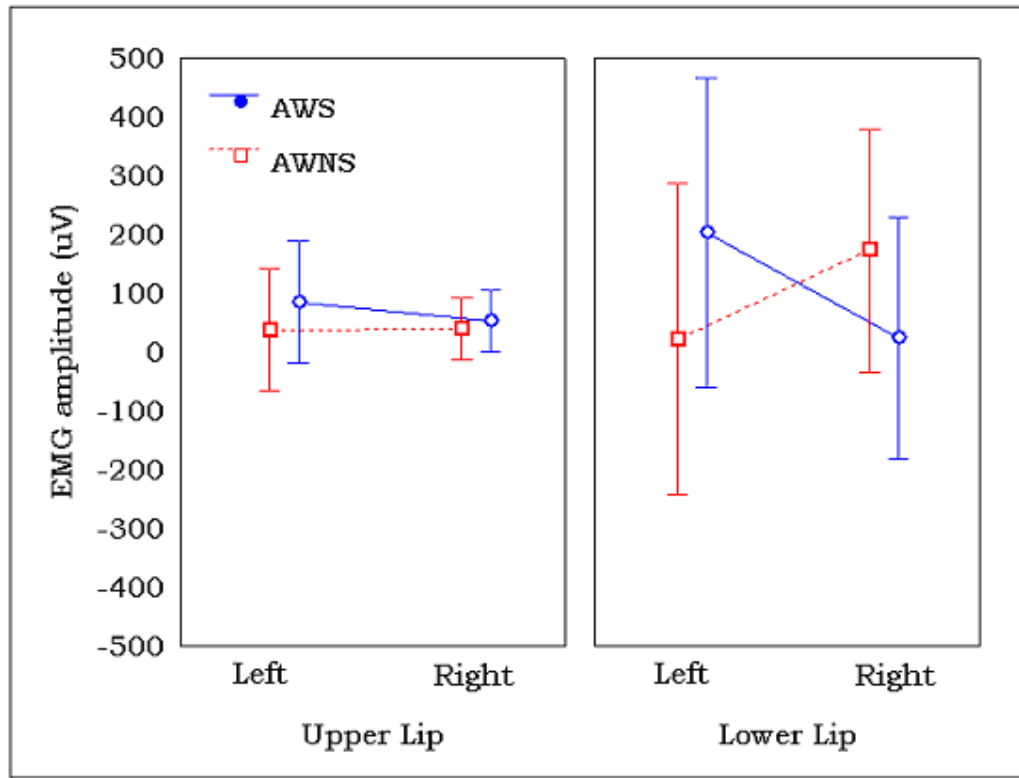


Figure 21. Depiction of result of three-way repeated-measures ANOVA analysis for EMG amplitude for lip pursing. The result of the 2 x 2 x 2 (AWS versus AWNS; left upper lip versus right upper lip; left lower lip versus right lower lip) ANOVA for the group-by-side interaction approached significance [ $F(1, 8) = 4.13, p = 0.077$ ]. The vertical bars denote 0.95 confidence intervals.

right EMG for each participant and then comparing those difference scores across the two groups. Results of the Mann-Whitney U test revealed a significant difference in the lower and then for the lower lips, in each case using a “difference score” between left EMG and lips between the LL and RL quadrants for the AWS and AWNS groups [ $U(n_1=5, n_2=5)=0$ ,  $p=0.004$ ]. No significant difference was found in the upper lips between the LU and RU quadrants [ $U(n_1=5, n_2=5)=10$ ,  $p=0.30$ ]. The difference score between the left EMG and right EMG for the upper and lower lips are depicted in Figure 22.

The peak EMG amplitudes obtained for each lip location are depicted in Figure 23 for the AWS participants and Figure 24 for the AWNS participants. The four lip sites were ranked in order of highest peak EMG activity. For the AWS group, three participants (AWS 2, 3 & 5) displayed the highest amplitude at the LL quadrant and the lowest amplitude at either the RU (AWS 2 & 3) or RL (AWS 5) quadrants. The two remaining participants (AWS 1 & 4) displayed the highest amplitude at RU quadrant and the lowest amplitude at the RL quadrant. The group mean amplitude for AWS was highest at the LL quadrant and lowest at the RL quadrant. Among the AWNS, four participants (AWNS 1-3 & 5) displayed the highest amplitude at the RL quadrant and the lowest amplitude at either the RU quadrant (AWNS 1) or LL quadrant (AWNS 2, 3 & 5). One participant (AWNS 4) displayed the highest amplitude at the LU quadrant and the lowest amplitude at the LL quadrant. The group mean amplitude for AWNS was highest at the RL quadrant and lowest at the LL quadrant.

In order to determine whether the EMG values of the various lip locations were correlated, a series of Pearson Product-Moment Correlation coefficients were calculated for each group. The results of the various correlations for the AWS and AWNS groups are shown in Table 10. Among the AWS group, only three comparisons for LU-LL, LU-RL, and LL-RL, were correlated ( $r=0.99$ ,  $p < 0.001$ ) indicating that when the peak amplitude

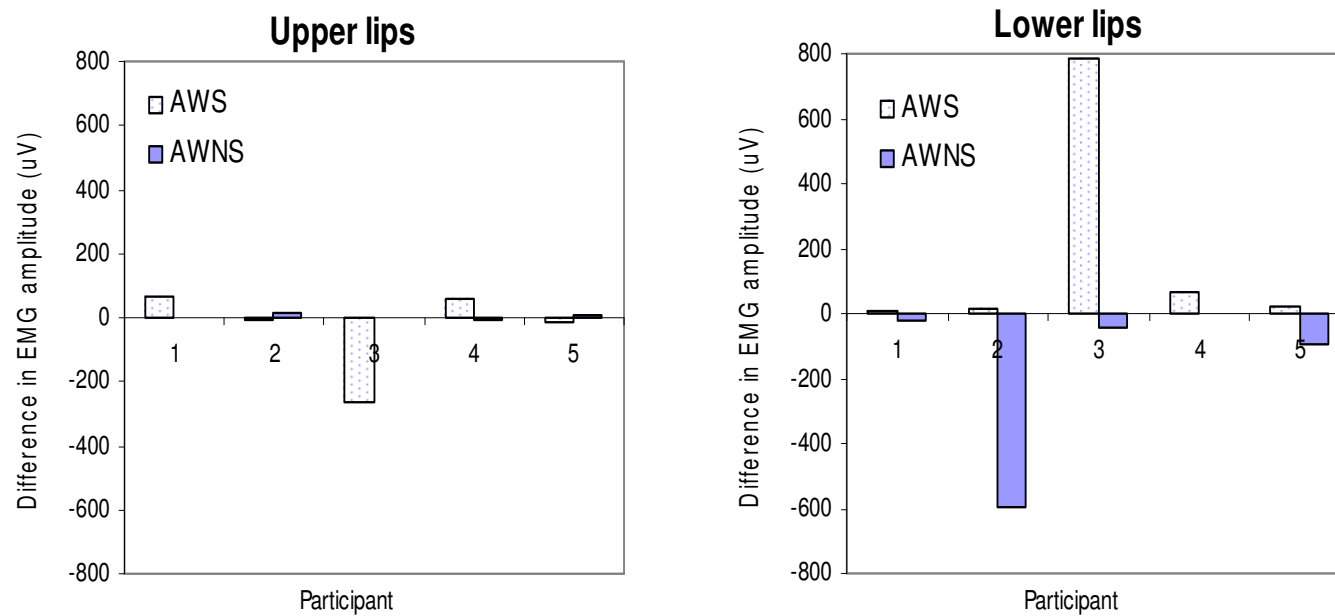


Figure 22. Histograms of the difference score for lip pursing for the upper and lower lips for adults who stutter (AWS) and adults who do not stutter (AWNS). The difference score for the upper lip was derived from the difference in EMG amplitude between the left upper (LU) and right upper (RU) lip quadrants. The difference score for the lower lips was derived from the difference in EMG amplitude between the left lower (LL) and right lower (RL) lip quadrants. Each pair of AWS and AWNS participant was sex- and age-matched.

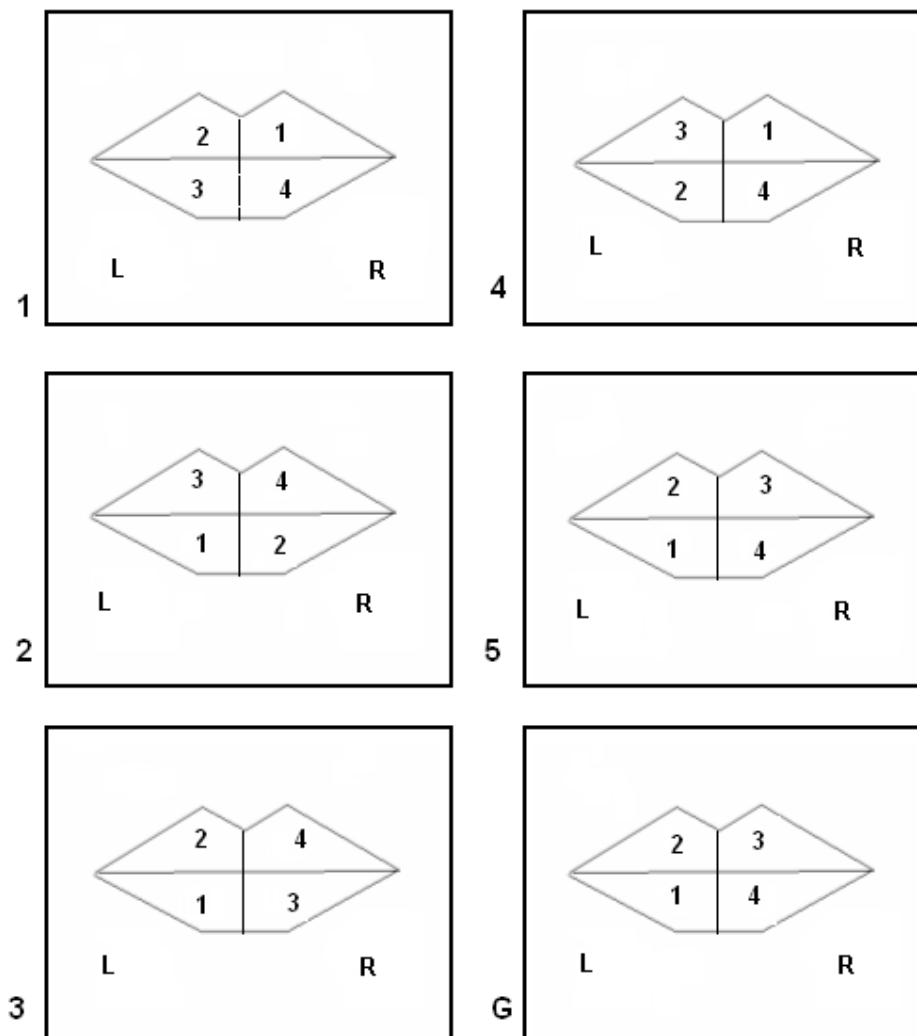


Figure 23. Diagram of peak amplitudes for the group of adults who stutter (AWS) recorded in the four quadrants of the lips for lip pursing. The quadrant with the highest peak amplitude is labeled '1' while the quadrant with the lowest peak amplitude is designated as '4'. Panel 1 and 2 reflect the peak amplitudes for participants 1 and 2, respectively. Panel 3, 4 and 5 reflect the peak amplitudes for participants 3, 4, and 5, respectively. Panel G reflects the mean amplitude for the AWS group.



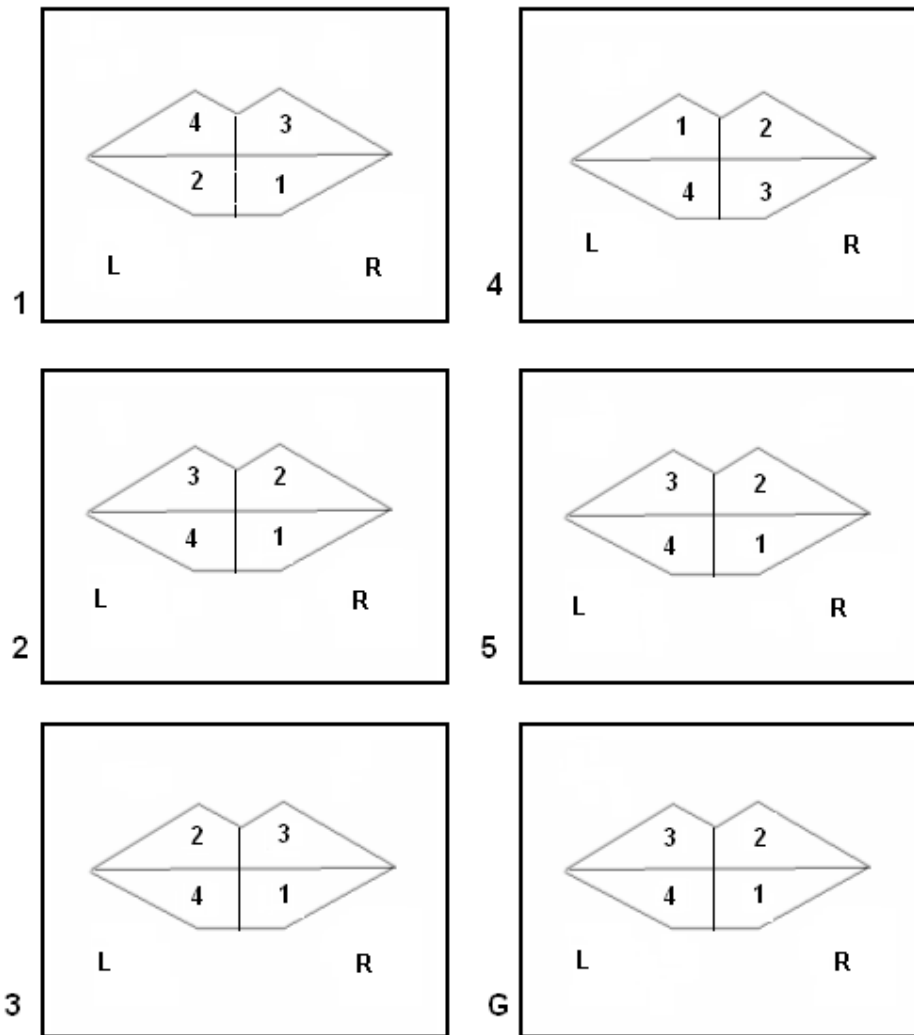


Figure 24. Diagram of peak amplitudes for the group of adults who do not stutter (AWNS) recorded in the four quadrants of the lips for lip pursing. The quadrant with the highest peak amplitude is labeled '1' while the quadrant with the lowest peak amplitude is designated as '4'. Panel 1 and 2 reflect the peak amplitudes for participants 1 and 2, respectively. Panel 3, 4 and 5 reflect the peak amplitudes for participants 3, 4, and 5, respectively. Panel G reflects the mean amplitude for the AWNS group.

Table 10. Correlation matrix for the adults who stutter (AWS) and adults who do not stutter (AWNS) for lip pursing. Correlations were calculated for the four lip quadrants: left upper (LU), right upper (RU), left lower (LL) and right lower (RL). Correlations in boldface were significant at the  $p<0.05$  level.

AWS				
LU	1.0			
RU	0.062	1.0		
LL	<b>0.998</b>	0.051	1.0	
RL	<b>0.997</b>	-0.013	<b>0.995</b>	1.0
	LU	RU	LL	RL

AWNS				
LU	1.0			
RU	<b>0.997</b>	1.0		
LL	<b>0.985</b>	<b>0.985</b>	1.0	
RL	<b>0.995</b>	<b>0.995</b>	<b>0.996</b>	1.0
	LU	RU	LL	RL

of one location was high, so too was the amplitude of the corresponding site. The other lip pairings were not significantly correlated including LU-RU ( $r = 0.062, p = 0.92$ ), RU-RL ( $r = -0.013, p = 0.98$ ) and RU-LL ( $r = 0.051, p = 0.935$ ). Visual representations of the significant correlations are shown in Figure 25. For the AWNS group, all possible lip comparisons were correlated ( $r \geq 0.98, p < 0.05$ ). A graphic representation of the correlation is shown in Figure 26.

*Summary of results.* In order to summarize the overall pattern of lip activity related to AWS and AWNS for both speech and non-speech tasks, the handedness laterality quotient, stuttering severity index (SSI) scores, and difference scores for the lower lips for /f/-word production, /p/-word production, single-sentence reading and lip pursing are presented in Table 11. The difference score was derived from the discrepancy in EMG amplitude between the left lower (LL) and right lower (RL) lip quadrants, and provides an indication of the disparity in muscle activity between the left lower lip and the right lower lip. A larger difference score would indicate greater discrepancy between the left lower lip and right lower lip activity. Two participants, AWS 3 and AWNS 2 consistently displayed the largest absolute difference score in their respective groups for all tasks. The handedness laterality quotient (%) as determined by the Edinburgh Handedness Inventory (Oldfield, 1971) related to the difference score for the lower lips for AWS and AWNS participants is provided in a scatter plot in Figure 27. The SSI related to the difference score for the lower lips for AWS and AWNS is provided in Figure 28. The SSI score for AWNS was arbitrarily set at one. In addition, a comparison of group mean amplitude for each lip location between AWS and AWNS for the different tasks is graphically depicted in Figure 29. The highest EMG amplitude was consistently displayed in the lower lip regions and was in opposition for both AWS and AWNS.

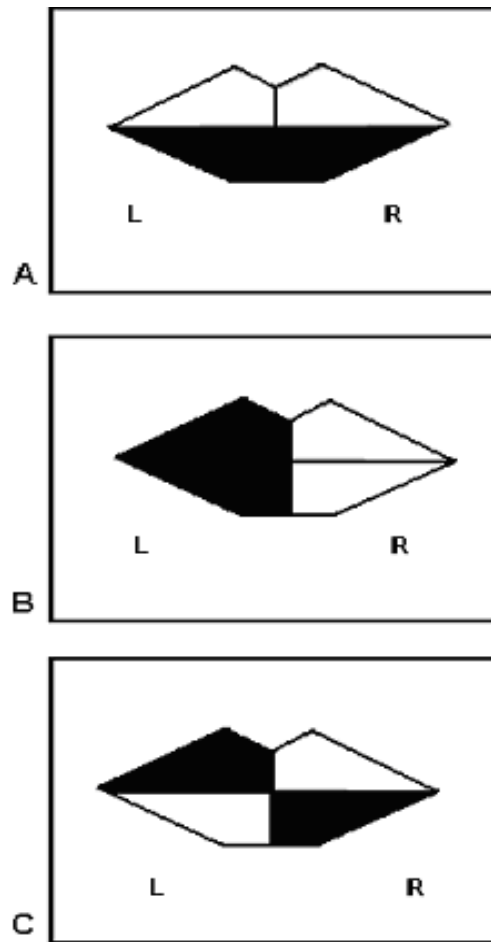


Figure 25. Depiction of significant correlation coefficients for lip quadrants for the group of adults who stutter (AWS) for lip pursing. Panel A and B reflect the correlated pairings of ipsilateral left lower and right lower (RL-LL) lips ( $r = 0.99, p < 0.001$ ) and left upper and left lower (LU-LL) lips ( $r = 0.99, p < 0.0001$ ), respectively. Panels C reflects the correlation for the diagonal pairing of left upper and right lower (LU-RL) lips ( $r = 0.99, p < 0.001$ ).

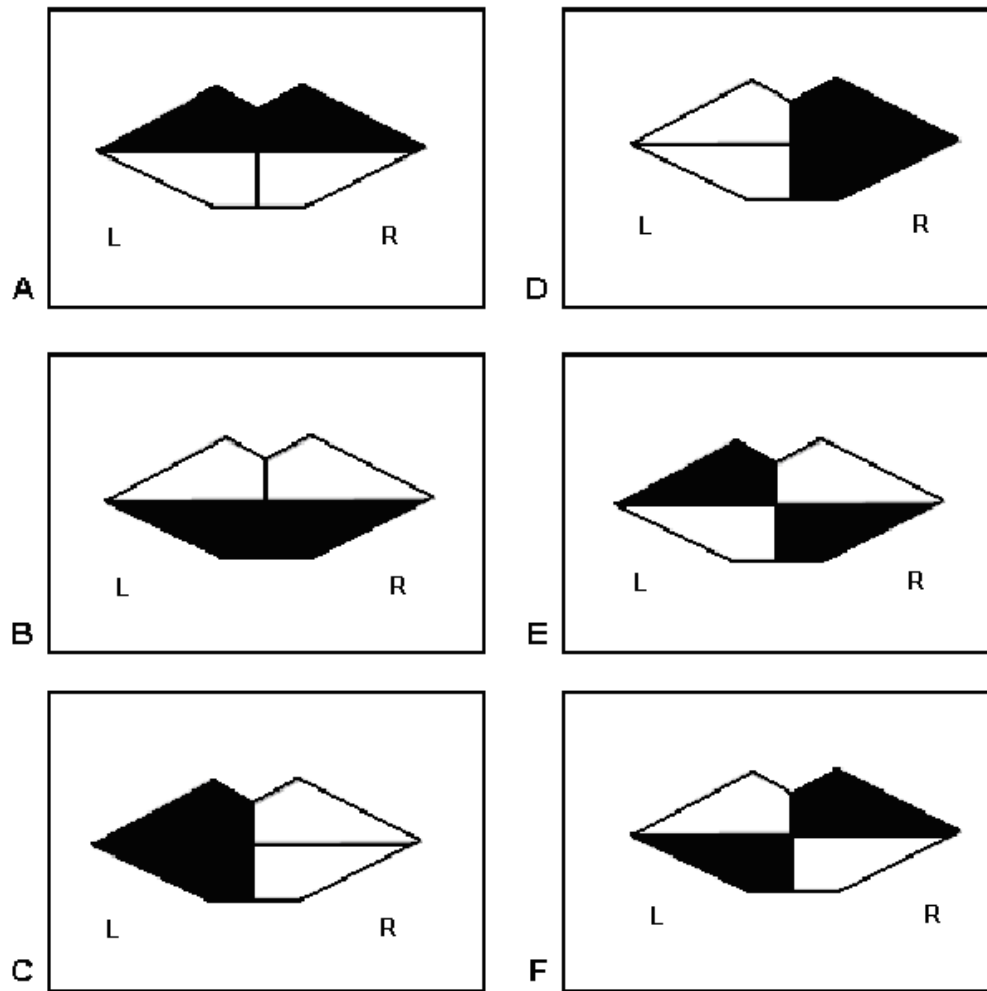


Figure 26. Depiction of significant correlation coefficients for lip quadrants for the group of adults who do not stutter (AWNS) for lip pursing. Panel A, B, C and D reflect correlations for the ipsilateral pairings of left upper and right upper (LU-RU) lips ( $r = 0.99$ ,  $p < 0.001$ ), left lower and right lower (LL-RL) lips ( $r = 0.99$ ,  $p < 0.001$ ), left upper and left lower (LU-LL) lips ( $r = 0.98$ ,  $p < 0.05$ ) and right upper and right lower (RU-RL) lips ( $r = 0.99$ ,  $p < 0.001$ ), respectively. Panels E and F reflect correlations for the diagonal pairings of left upper and right lower (LU-RL) lips ( $r = 0.99$ ,  $p < 0.001$ ) and right upper and left lower (RU-LL) lips ( $r = 0.98$ ,  $p < 0.05$ ), respectively.

Table 11. Handedness, stuttering severity index (SSI) score, and difference score for the lower lips in microvolts ( $\mu V$ ) for /f/-word production, /p/-word production, single-sentence reading and lip pursing for adults who stutter (AWS) and adults who do not stutter (AWNS).

AWS						
Participant	Handedness*	SSI Score	Difference score** ( $\mu V$ )			
			/f/	/p/	sentence	lip purse
1	100%	20	2.99	-0.8	9.54	6.4
2	60%	6	9.30	23.39	10.15	17.57
3	100%	15	280.53	167.04	471.68	785.45
4	100%	24	32.25	28.62	23.93	63.81
5	60%	21	15.59	15.29	17.41	20.92

AWNS						
Participant	Handedness*	SSI Score	Difference score** ( $\mu V$ )			
			/f/	/p/	sentence	lip purse
1	100%	–	-15.10	-12.55	-26.55	-20.95
2	88.9%	–	-402.54	-171.98	-399.08	-597.02
3	100%	–	-88.48	-33.53	-55.07	-45.56
4	100%	–	-2.98	0.11	-0.42	-2.5
5	88.2%	–	-31.34	-29.82	-35.32	-90.97

\* all participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971).

\*\* The difference score was derived from the difference in EMG values between the left lower (LL) and right lower (RL) lip quadrants.

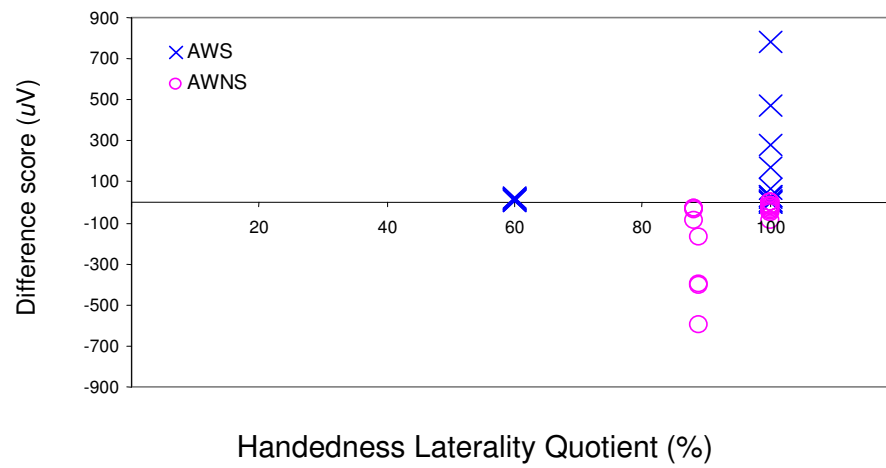


Figure 27. Difference score for the lower lips in microvolts ( $\mu\text{V}$ ) and handedness laterality quotient in percent for all speech and non-speech tasks. The difference score was derived from the discrepancy in EMG amplitude between the left lower (LL) and right lower (RL) lip quadrants. All participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971).

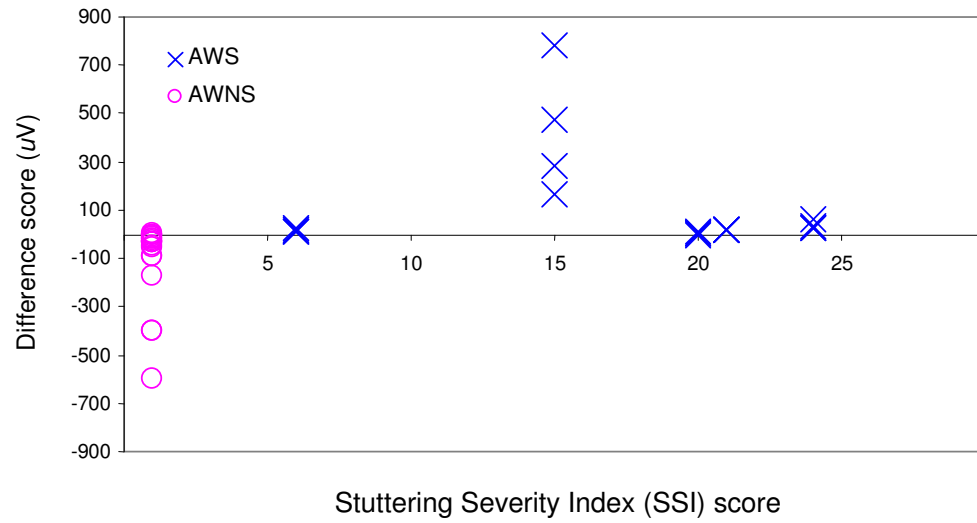


Figure 28. Difference score for the lower lips in microvolts ( $\mu V$ ) and stuttering severity index (SSI) score for adults who stutter (AWS) and adults who do not stutter (AWNS). The difference score was derived from the discrepancy in EMG amplitude between the left lower (LL) and right lower (RL) lip quadrants. The SSI score of AWNS was arbitrarily established at one.



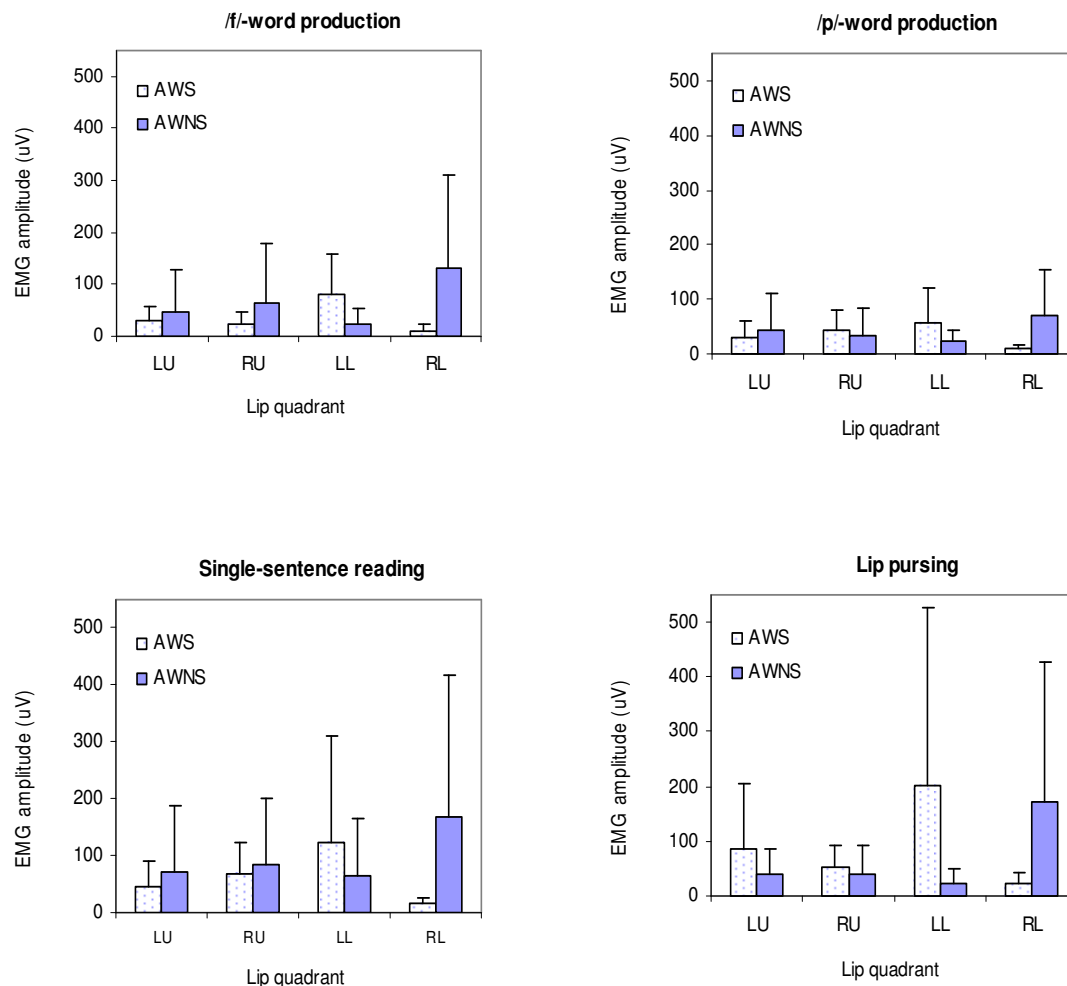


Figure 29. Histograms of group mean electromyographic (EMG) amplitudes for upper (LU & RU) and lower (LL & RL) lip quadrants for the group of adults who stutter (AWS) and adults who do not stutter (AWNS) for /f/-word production, /p/-word production, single-sentence reading, and lip pursing.

## Summary of Major Findings

- (1) Across the AWS participants, the right lower (RL) location yielded the lowest EMG amplitude for all speech and non-speech tasks. While the highest EMG amplitude for the AWS group was at the left lower (LL) location.
- (2) Across the AWNS participants, the left lower (LL) location yielded the lowest EMG amplitude for all speech and non-speech tasks. While the highest EMG amplitude for the AWNS group was at the right lower (RL) location.
- (3) Among the AWS group, the peak EMG amplitudes collected at the various lip sites during speech production tasks were not correlated with the exception of the left upper and left lower (LU-LL) lip pairing. For the non-speech task, only three lip comparisons were correlated: left upper and left lower (LU-LL), left upper and right lower (LU-RL) and right lower and left lower (RL-LL).
- (4) Among the AWNS group, the peak EMG amplitudes collected at the various lip sites during both speech and non-speech tasks were significantly correlated.

## **Discussion**

### **Stuttering and Laterality**

As early as the 1920s' Orton and Travis espoused the view that stuttering was a consequence of aberrant laterality. More recently, a number of EEG investigations (Moore, 1984; Wells and Moore, 1990) and neuroimaging studies utilizing functional magnetic resonance imaging (fMRI), positron emission tomography (PET) and magnetoencephalography (MEG) techniques (Biermann-Ruben et al., 2005; Blomgren et al., 2003; Braun et al., 1997; De Nil et al., 2000; Neumann et al., 2003; Preisbich et al., 2003; Salmelin et al., 2000; Van Borsel et al., 2003; Walla et al., 2004) have found atypical laterality and activation associated with stuttering as initially speculated by Orton and Travis. These studies reported lateralization of speech processing to the right cerebral hemisphere in AWS during fluent speech production and moments of stuttering. For AWNS, speech processing was left hemisphere lateralized.

The purpose of the present study was to investigate differences in cerebral activation between AWS and AWNS as inferred by measurement of EMG lip activity. Despite the relatively small sample size, the pattern of EMG signal observed in the present study provides strong support for the hypothesis of anomalous cerebral laterality in AWS and also the use of EMG as an indication of cerebral participation at the moment of speech production. Measurements of peak EMG amplitude were obtained at four lip locations: LU, RU, LL and RL. Analysis of the data indicated there were significant differences between the AWS and AWNS groups in regard to the peak EMG amplitude between the left and right sides of the lips across all speech and non-speech tasks. There was a pattern in which the lowest EMG amplitude for the AWS and AWNS groups were located at the RL and LL quadrants, respectively. The highest EMG amplitude for the AWS and AWNS groups were located at the LL and RL quadrants, respectively. That is, for both groups the

highest and lowest peak EMG activity was found in the lower regions of the mouth. This observation is consistent with several EMG studies that have reported higher activity for the lower than upper lips (Kelly et al., 1995; van Lieshout et al., 1993; Wohlert & Goffman, 1994). In the present study, the specific lip location for the highest and lowest EMG amplitude was in direct opposition for AWS and AWNS. AWS displayed the highest EMG activity in the left lower (LL) lip while AWNS featured the highest activity in the right lower (RL) lip. This pattern of lip activity for AWS and AWNS is in concordance with previous investigations and assumed to be a corollary of differences in cerebral activation between the two groups (Code et al., 2005; Graves et al., 1982). In AWS, the higher amplitude and significantly correlated EMG activity observed on the left side of the mouth is an indication of right cerebral activation during the execution of speech and non-speech movements and substantiates previous investigations reporting lateralization of speech processing to the right hemisphere in AWS (Braun et al., 1997; De Nil et al., 2000; Wells & Moore, 1990). As expected, a reversal of lip activity was observed in AWNS with elevated EMG levels featured on the right side of the mouth, indicative of left cerebral lateralization for speech processing (Graves et al., 1982). The results of the present study do not suggest the exclusion of one hemisphere in favor of the other during speech or non-speech production. EMG activity observed on both sides of the mouth (although in varying degrees) in AWS and AWNS is suggestive of participation from both hemispheres during speech and non-speech tasks. The documented pattern of EMG reduction on one side of the mouth and elevated activity on the opposite side is suggestive of unequal participation or lateralization of the cerebral hemispheres during speech and non-speech production.

The results of the correlation analysis were also suggestive of distinct patterns of EMG activation for each group. Among the AWNS group, all combinations of lip pairings of the four mouth locations were highly correlated with one another for both speech and

non-speech tasks. These patterns of correlation were taken to indicate that AWNS demonstrated highly coordinated lip muscle activity across all tasks. Interestingly, no such pattern was found for the AWS group with the exception of the LU-LL sites which were consistently correlated during speech and non-speech tasks. In fact, negative correlations were found for some lip muscle pairings (see Table 4, 6, & 10), substantiating the lack of synchrony between muscle groups. The lack of correlation in AWS compared to AWNS may indicate greater hemispheric interference or reduced performance as a consequence of right cerebral contribution since the right hemisphere is better suited for non-linguistic processing (De Nil & Kroll, 2001; De Nil et al., 2003; Moore, 1984; Webster 1990). This is also evident by the fact that the lip pursing exercise in AWS which is a non-linguistic task generated a slightly greater number of positively correlated lip pairings (LU-LL, LU-RL and LL-RL) in comparison to the speech tasks (/f/-word production, /p/-word production and single-sentence reading) which only produced a single positive correlation (LU-LL). Reduced correlation levels in AWS may be suggestive of reduced strength of neural pathway connectivity (McClean & Tasko, 2004). In the present study, reduced correlation levels in AWS may be a consequence of weak connectivity between the distinct quadrants of the lips. The EMG locations on the left side of the mouth in AWS were also the locations that tended to show the largest EMG amplitudes compared to the sites on the right side of the mouth. Therefore, while the AWNS seemed to show generally high levels of EMG activation on both the left and right sides of the mouth, the AWS group showed a tendency for the highest activation only on the left side of the mouth. Interestingly, several studies have reported higher quality of articulation out of the right side of the mouth when compared to the left (Cadallbert et al., 1994; Graves & Potter, 1988). Therefore, one would expect AWS to demonstrate reduced quality of articulation if the only correlated lip pairing (LU-LL) which might contribute unevenly to speech production is located on the left side

of the mouth. The reduced correlation displayed by AWS in the present investigation corroborates past studies suggesting reduced motor coordination (Hulstijn et al., 1992; Smith, 1989; van Lieshout et al., 1996b).

It is interesting to note that the single highest documented EMG amplitude observed within the AWS group for each task was consistently presented by the same participant (AWS 3). In addition, within the AWS group that same participant (AWS 3) also presented the greatest difference in EMG activity between the left (LL) and right lower (RL) lip quadrants as indicated by the difference score (see Figure 4, 10, 16 & 22). Eight months prior to participation in the present study, AWS 3 had completed the Camperdown program, a treatment based on prolonged speech which resulted in significant improvements to his fluency (O'Brian et al., 2003). Interestingly, in both speech and non-speech tasks, AWS 3 presented greater RL lip amplitude than the group mean (see Tables 3, 5, 7 & 9). The elevated RL lip amplitude in AWS 3 is consistent with reports of greater left hemisphere participation following treatment (Boberg et al., 1983; De Nil et al., 2003). In addition, AWS 3 also featured greater LL amplitude in comparison to the group mean which is indicative of elevated right hemisphere participation for all tasks (see Tables 3, 5, 7 & 9). Although this pattern might seem in conflict with observations of reduced right hemisphere participation following treatment (Boberg et al., 1983; De Nil et al., 2003), the plausible explanation may be linked to increased compensation for fluent speech. Giraud et al. (2008) observed lower activation of the right frontal operculum in AWS who were less fluent and higher activation in AWS who were more fluent. In AWS 3 (who presented greater fluency after therapy), the elevated activity of the right hemisphere is probably due to increased compensatory activity of the right frontal operculum (Giraud et al., 2008; Preibisch et al., 2003).

In the present study, two AWS (2 & 5) individuals demonstrated the weakest right hand preference (Handedness Laterality Quotient of 60%) observed for either group. Individual handedness laterality scores in AWNS participants were equal or higher than those reported in AWS (see Table 11). Further, there maybe a subtle pattern whereby AWNS who displayed stronger lateralization for right hand preference were more likely to demonstrate a smaller difference score or less discrepancy between left and right cerebral activity (see Figure 27). In AWNS, stronger right hand lateralization has been directly linked to greater left hemisphere dominance for language and vice versa (Knecht et al., 2000). In addition, AWNS who were more lateralized for hand preference and language processing may also display greater lateralization for other types of processing including visual stimuli. Therefore, the visually presented instructions and tasks in the present study may have resulted in greater right hemisphere activity in AWNS who were more strongly lateralized in hand preference than AWNS who were less lateralized. Subsequently, AWNS who are strongly lateralized in hand preference may present reduced discrepancy in activation levels between the left hemisphere (involved in speech processing) and right hemisphere (involved in visual processing) resulting in a smaller difference score. The right hemisphere is expected to participate in visual processing in AWNS and AWS (Boberg et al., 1983).

In contrast, AWS participants who displayed stronger lateralization of hand preference maybe be more likely to demonstrate greater discrepancy between the left and right cerebral activity as indicated by the LL and RL lip activity (see Figure 27). However, AWS with weaker right hand preference may be more likely to display a smaller difference score suggesting greater similarity between the left and right cerebral contribution. In the present study, right hemisphere participation is expected for both processing of speech and visually presented stimuli in AWS. Thus, the disparity between participation of the left and

right cerebral hemispheres, particularly in AWS who are strongly lateralized may be elevated as a consequence of right hemisphere participation for both speech and visual processing. In AWS, larger values of the difference score was a product of greater amplitude displayed by the left lower lip (see tables 3, 5, 7 & 9). This pattern related to hand lateralization in both groups must be considered with extreme caution due to the small sample size.

Previous research examining lip EMG activity in AWNS has yielded equivocal results. In a reading task of the Grandfather Passage (similar to the present study), Wohlert and Hammen (2000) reported that most individuals were “right-mouthed”, recording higher EMG activity on the right upper lip. Their findings supported previous studies documenting lip asymmetry by Graves and colleagues (Graves et al., 1982; Graves & Potter, 1988). In contrast, Wohlert and colleagues (Wohlert & Goffman, 1994; Wohlert & Smith, 2002) failed to find similar mouth asymmetry during speech and non-speech movements. The lack of agreement between these studies was one of the motivations behind the current research. Based on results obtained from the present group of AWNS participants, evidence is provided in support of Graves and colleagues indicating lip asymmetry across tasks. While the present results are suggestive of lip asymmetry in AWNS, it remains to be determined why Wohlert and colleagues failed to identify lip asymmetry. One possibility to consider is the age of participants involved. In the study by Wohlert and Smith, participants comprised of 29 young adults (average age of 20.9 years) and 60 children ranging from seven years of age to 12 years of age. Although language lateralization occurs early in human development (Holowka & Pettito, 2002), children are less lateralized and display greater variability in lateralization when compared to adults (Holland et al., 2001, 2007). The degree of lateralization increases with age and is assumed to reflect improvements in language skills and greater specialization of language functions



(Hoeft et al., 2007; Holland et al., 2001, 2007). Since lip activity and asymmetry is linked to cerebral lateralization, it is not surprising that the study by Wohlert and Smith which comprised mainly of children failed to find lip asymmetry. In the present study, the mean age of the AWS and AWNS participants were 26 years and 25 years, respectively. In addition, the degree of lip asymmetry may also be related to gender. In their study of perioral muscle activity, Wohlert and Goffman recruited three male and five female participants. Females are less lateralized than males and show more bilateral activation for language processing (Bourne, 2005; Kent, 1998; McGuiness & Bartell, 1982). This is evident in several investigations of lip activity where females tended to be less asymmetrical than males (Graves et al., 1982; Hausmann et al., 1998). Additionally, male faces are structurally more asymmetrical than female faces even at rest (Schmidt et al., 2006). Therefore, investigations comprising of only males participants, or equal or larger ratio of male to female participants are more likely to document lip asymmetry (Borod et al., 1988; Code et al., 2005; Graves et al., 1982; Wohlert & Hammen, 2000). Further, studies employing video image technique have consistently reported lip asymmetry (Code et al., 2005; Graves et al., 1982; Graves & Landis, 1990; Hausman et al., 1998) whilst those measuring EMG signals have produced ambivalent results (Wohlert & Goffman, 1994; Wohlert & Hammen, 2000; Wohlert & Smith, 2002). Therefore, it is likely that reports of lip asymmetry are influenced by age, gender and even the method of evaluation.

The finding of the present study is consistent with previous investigations documenting lip asymmetry in AWNS (Graves et al., 1982; Graves & Potter, 1998; Hausmann et al., 1998; Nicholls et al., 2004). Right lip asymmetry observed in AWNS is assumed to be a corollary of the left cerebral specialization for language (Beeman & Chiarello, 1998; Chiarello et al., 2006; Hausmann et al., 1998; Kent, 1998; Nicholls & Searle, 2006). Interestingly, human babies feature right mouth asymmetry during babbling,

which is suggestive of left cerebral lateralization even during pre-linguistic stages of human language development (Holowka & Pettito, 2002). In contrast, a left lip bias suggests that language processing is right hemisphere lateralized in AWS which corroborates past investigations into stuttering (Biermann-Ruben et al., 2005; Blomgren et al., 2003; Braun et al., 1997; Code et al., 2005; De Nil et al., 2000; Neumann et al., 2003; Preisbich et al., 2003; Salmelin et al., 2000; Van Borsel et al., 2003; Walla et al., 2004).

Additionally, the link between stuttering and emotion in AWS cannot be dismissed (Bloodstein, 1987; Craig et al., 2003; Ezrati-Vinacour & Levin, 2004; Guitar, 1997, 2003, 2006; Menzies et al., 1999; Messenger et al., 2004; Miller & Watson, 1992). AWS often link their stuttering to emotional reactions and report anticipatory anxiety prior to speech production particularly in high stress situations (Alm, 2004). Past emotional conditioning associated with speech production may result in overactivation of the right cerebral hemisphere (Boberg et al., 1983). In addition, there is evidence suggesting that changes in language use may occur after fluency treatment which may be indicative of changes in attitude towards speech production (Spencer et al., 2005). AWS have been reported to shorten conversations in order to avoid stuttering (Corcoran & Stewart, 1998, as cited in Spencer et al., 2005). Following treatment, AWS have been observed to increase the use of modality in their conversation. Modality is an expression of indeterminacy which communicates opinions and attitudes (Halliday, 2004; Spencer et al., 2005). Modalities such as *I think...*, *I don't believe...*, and *Couldn't it be?* prolong the conversation between speaking partners (Spencer et al., 2005). This finding related to language use suggests that attitudes and emotions play a crucial role in speech production in AWS. In addition, the right cerebral hemisphere which is dominant for language processing in AWS has also been associated with emotional processing (Borod et al., 1988; Bourne, 2005; Davidson et al., 2004; Killgore & Yurgelun-Todd, 2007). Code et al. (2005) suggested that activation of

the right hemisphere in AWS maybe linked to emotion specifically anxiety, as a result of directed attention to speech production. Thus, emotion associated with speech production is considered in the following sections.

### **The Right Hemisphere Hypothesis**

One of the original hypotheses to be tested in the present study was the Right Hemisphere Hypothesis. This hypothesis was based on previous work related to emotion and facial expression. The general premise of the hypothesis is that all emotional processing is lateralized to the right cerebral hemisphere and thus displayed more intensely on the left side of the face as a result of contralateral innervation (Borod et al., 1988). Although this is the first such study to link aspects of normal and disordered speech production to this hypothesis, two possible outcomes were expected. First, assuming speech is a form of emotional expression, it was expected that both AWNS and AWS would show lip EMG dominance on the left side of the face. Alternatively, it was proposed that AWS might show significantly more left-side dominance compared to AWNS because of the strong negative emotions associated with the anticipation and execution of speech.

In the present study, there was a pattern of elevated EMG activity on the left side of the mouth in AWS which is indicative of right cerebral participation. This finding is further reinforced by the significant correlation between LU and LL EMG signals for the AWS speakers. The neurophysiological phenomenon of contralateral innervation of facial muscles means that cerebral participation of one hemisphere will feature prominently on the contralateral side of the mouth. Since the Right Hemisphere Hypothesis asserts that the right cerebral hemisphere is dominant for emotional expression, greater left mouth activity as a consequence of greater right cerebral participation in AWS maybe a product of emotions related to speech (Cowie & Cornelius, 2003). Past research investigating the

psychological aspects of stuttering have cited negative emotions as a component of the stuttering experience (Craig et al., 2003; Ezrati-Vinacour & Levin, 2004). A classic theory of stuttering, the Anticipatory-Struggle Hypothesis (Bloodstein, 1987) credits negative emotion as the source of stuttering. The supposition of this classic theory is relevant to the present study as all AWS participants reported that they found speech production to be a relatively negative experience. Interestingly, more recent research has reported higher anxiety levels and also increased reactivity in AWS (Alm & Risberg, 2007; Guitar, 2003). The results of the present study obtained from the EMG data, paired with the anecdotal reports by the AWS participants, is consistent with the Right Hemisphere Hypothesis and the notion of right lateralized cerebral processing of emotion.

Conversely, speech production was not expected to evoke negative emotions but either a neutral or positive experience in AWNS. In the present study, all lip sites showed highly correlated EMG amplitude, with the highest amplitude on the right side of the face which is indicative of left hemisphere dominance for both speech and non-speech tasks. AWNS participants featured reduced left lip activity or right hemisphere participation in comparison to AWS participants which maybe suggestive of a lack of emotion (either positive or negative) related to speech production. Additionally, several studies have reported a larger right mouth bias during speech tasks similar to those employed in the present study than simple repetitive oral movements (Caldabert et al., 1994; Wohlert & Goffman, 1994). In the present study, the pattern of cerebral activation related to emotion during the non-speech task is assumed to be an effect of the instructions given for the task. For non-speech samples, participants were asked to purse their lips as they would when saying the word “pool”. The instructions would suggest similar processing for both speech and non-speech tasks during the initial stages but with suppression of vocalization at the final juncture for the latter task. Consequently, the non-speech task is expected to generate

similar cerebral activation and associated emotions to those of the speech tasks in both AWS and AWNS.

### **The Valence Hypothesis**

The other emotion-based hypothesis evaluated in the present study is the Valence Hypothesis which makes a distinction between cerebral processing of positive and negative emotions. This hypothesis predicts that negative emotions will be processed in the right cerebral hemisphere while processing of positive emotions will be lateralized to the left hemisphere. The assumption in the present study was that requiring AWS to complete a series of speech and non-speech tasks would evoke negative emotion. Therefore, the Valence Hypothesis would predict greater EMG activity on the left side of the mouth of AWS participants as a result of cerebral lateralization of negative emotion. The significant differences between AWNS and AWS in lower lip EMG amplitude in the present study, was taken as support for the Valence hypothesis. The pattern of EMG activity documented in AWNS participants can be interpreted in two ways. Firstly, the high correlation among the four sites is suggestive of absent or reduced negative feelings associated with speech. Alternatively, the consistently high EMG amplitude on the right side of the face indicative of left cerebral activity would be suggestive of positive emotions related to speech. In AWS, the elevated EMG on the left side of the mouth can be construed as greater right cerebral participation. Additionally, the significant correlation between LU and LL EMG signals for the AWS speakers also confirmed lateralization on the left side of the mouth. This pattern of left lip asymmetry can be interpreted as the presence of negative feelings associated with speech in AWS.

The suggestion that both the Right Hemisphere Hypothesis and Valence Hypothesis are supportive of the present findings is not necessarily a contradiction. Killgore and

Yurgelun-Todd (2007) speculate that cerebral processing of emotion may occur in parallel and is task dependent. In their study, participants were presented with chimeric sad (half sad/ half neutral) and chimeric happy (half happy/half neutral) faces to their left and right visual fields. For left visual presentations, regardless of emotion type, the right cerebral hemisphere was reliably activated (although greater activation was detected for negative emotion), thereby providing evidence for the Right Hemisphere Hypothesis. When happy chimera was presented to the right visual field, cerebral activation was detected in the left hemisphere, providing support for the Valence Hypothesis. Interestingly, presentation of sad chimera to the right visual field activated both hemispheres. These findings based on right visual field presentations are consistent with the Valence Hypothesis while those of the left visual field substantiate the Right Hemisphere Hypothesis. Based on these results, Killgore and Yurgelun-Todd advocate a unified model of processing where the right cerebral hemisphere is dominant for processing emotion regardless of valence with the left hemisphere operating in limited capacity.

### **Other Basis for Lip Asymmetry**

Additionally, Wolf and Goodale (1987) posit that the observed asymmetry is a consequence of the efficiency of the right lip in initiating movement as a result of direct neural access. The contralateral pathway is functionally stronger than the ipsilateral pathway (Kent, 2004b). In other words, lip asymmetry is a corollary of the direct and stronger connection of the right lip to the left cerebral hemisphere which is responsible for sequenced oral movement (Wohlert & Goffman, 1994). The right lip is also anticipated to open slightly larger than the left lip at any given time since it initiates movement sooner than the left lip (Nicholls & Searle, 2006). In addition, functional muscle asymmetry of the lips may result from asymmetry of muscle strength or development. For example,

asymmetry of gait is associated with asymmetry of muscle strength (Maupas et al., 2002). In most right-handed individuals, the right side of the body is stronger and the right limb initiates movement while the left limb is responsible for support (Sadeghi et al., 2000). Accordingly, lip asymmetry may be associated with asymmetry of facial muscle strength. Graves and Landis (1990) reported a higher number of right lip asymmetry in right-handed than left-handed AWNS males which suggest that lip asymmetry may feature a similar trend to limb asymmetry. The right lip may initiate movement due to greater muscle strength. Accordingly, AWS may feature greater strength on the left side of the face and initiate movement with the left lip. Furthermore, initiation of lip movement may be coupled with the timing of cerebral activation. In several investigations of verbal and non-verbal oral movement in AWNS, activation of the left cerebral hemisphere preceded the right (Palolahti et al., 2005; Saarinen et al., 2006). Hence, earlier initiation of right mouth movement may be a consequence of earlier activation of the left cerebral hemisphere. Accordingly, the reversed pattern of lip asymmetry in AWS may suggest reduced connection between the right lip and left cerebral hemisphere, reduced right facial muscle strength, and/or activation of the right cerebral hemisphere prior to the left.

Although structural asymmetry of facial muscles at neutral expression does not offer a complete explanation for lip laterality, it does however offer further insight into laterality associated with muscle activity. Schmidt et al. (2006) found male faces to be structurally more asymmetrical than female faces even at rest. Males tended to have larger left faces. Not surprisingly, the lateralization of facial expression was directly affected by the degree of asymmetry of neutral facial expression. Therefore, lip asymmetry in the present study may have been bolstered by the recruitment of only male participants.

## **Limitations**

The limitations of the present study discussed in the sections below include those related to participant recruitment, speech muscles, rate and intensity variations, data analysis and the nature of speech and non-speech tasks.

### **Participant Recruitment**

In the present study, only five participants were recruited for each group. Similar research (Wohlert & Goffman, 1994; Wohlert & Hammen, 2000; Wohlert & Smith, 2002) investigating lip muscle activity enlisted twice the number of individuals than the present study. Although, differences were found between AWS and AWNS in regard to lip activity, the result must be interpreted with caution due to the small sample size. The heterogeneity of AWS as a group calls for a larger sample size. In addition, results of the present study cannot be generalized to female AWS who have been documented to be less lateralized than AWS males for speech processing (Ingham et al., 2004).

Previous brain imaging studies of AWS have reported greater activation of the right cerebral hemisphere specifically the right front operculum as a compensatory mechanism (Giraud et al., 2008; Preisbich et al., 2003). AWS with less severe stuttering demonstrate greater activation of the right frontal operculum than AWS who are more severe (Giraud et al., 2008). Thus, the participants in the current study who ranged from very mild to moderate severity may only be a small subset of the AWS population who feature left lip asymmetry as a consequence of greater activation of the right frontal due to increased compensation.

The present study did not consider differences in fluency treatment programs related to the AWS. Although more volitional control of speech processes is common to most fluency treatment programs, the specific nature of the programs may differ. In the



present study, most of the AWS (2, 3 & 4) participants utilized the prolonged-speech technique which is the basis of the Camperdown program while one participant (AWS 5) utilized the costal breathing technique advocated by the McGuire program. Due to the small sample size of the current study, direct comparisons cannot be made between the two programs in the present study. However, both treatments resulted in varying degrees of reduced speech naturalness. For future investigations, the specific nature of treatment programs utilized by participants should be considered as they directly alter the physical aspects of speech production (Tasko et al., 2007).

### **Speech Muscles**

Although surface electrodes have the benefit of being non-invasive, that same characteristic means that the recorded EMG signal is likely a composite of activity from more than one muscle (McClean & Tasko, 2003). Therefore, interpretations involving single muscle recruitment must be made with caution. The EMG signals recorded in the present study are likely to be a composite of various muscle activity in the vicinity of the OO that insert into the upper lip (Blair & Smith, 1986; Stegeman et al., 2000). Also, individual variations in muscle size and orientation impact electrode placement and consequently, measurements of muscle recruitment (Wohlert & Smith, 2002). Anatomical variables such as fat layer distribution and skin characteristics vary between- and within- individuals and may confound evaluations of asymmetry (Fridlund, 1988; Wohlert & Hammen, 2000).

Secondly, speech production is an amalgamation of various systems and musculature that requires precise coordination. Stuttering has been described as a disintegration of articulatory coordination (Loucks et al., 2007). Therefore, to obtain a clearer picture of speech production and cerebral control, other speech structures must be

evaluated concurrently with the upper and lower lips. Besides the OO, Shapiro (1980) observed high levels of muscle activity in the larynx and tongue of AWS. Additionally, excessively high EMG activity of the jaw muscle has been cited (Kalotkin et al., 1979). These results of these studies advocate the importance of evaluating multiple systems related to speech production in addition to the upper and lower lips to accurately assess neural input and coordination in AWS.

### **Rate and Intensity Variations**

EMG amplitudes are directly correlated with speech rate and intensity. Increases in speech rate and loudness will increase EMG amplitude (Wohlert & Hammen, 2000). Additionally, the rate of speech has been documented to influence cerebral activation (Munhall, 2001). In the present study, participants were asked to read at their habitual rate and loudness but there may be considerable variability in “habitual” speaking rate and loudness between individuals. This was clearly evident in the present study. The lowest and highest recorded amplitude for the speech tasks were 4.41  $\mu$ V (AWS 2 during /f/-word production) and 663.28  $\mu$ V (AWNS 2 during single-sentence reading), respectively. The varying levels of loudness and speed related to individual variations in “habitual” speaking conditions may have served to confound the EMG signal. This is postulated to be particularly acute in the present study where all of the AWS participants have reported a history of speech therapy. Most fluency enhancing programs employ slow rate of speech as a technique (Andrews et al., 1983). Reduced rates of speech will result in lower EMG amplitudes. In the present study, although the locations of the highest and lowest EMG values were in opposition for AWS and AWNS, visual inspection of the data suggests that the absolute values of the EMG signal without regard to location were not significantly different. This is in contrast to past AWS investigations that have reported excessive

muscle activity in numerous speech structures including the lips (Platt & Basili, 1973; Shapiro, 1980; van Lieshout et al., 1993, 1996a). Therefore, it is likely that in the present study, the EMG signal was affected by fluency treatment. Previous research has shown that a decrease in speech rate can be accompanied by a decrease in intensity (McClean & Tasko, 2003). It is possible that AWS in the present study presented reduced rate of speech as a consequence of fluency treatment which would result in reduced EMG amplitudes.

### **Data Analysis**

Although, the measurement of peak EMG amplitude employed in the present study was an indicator of the highest amplitude of lip muscle activity, it may not accurately predict or reflect overall movement of the perioral muscles during speech and non-speech tasks. An alternative approach would have been to consider the changes in EMG signal, which is presumed to be a direct gauge of the variability in cerebral input and muscular effort (Ingham et al., 2006; Wohlert & Smith, 2002). However in the present study, only ten samples for each phoneme or sentence production were available for analysis. The low sample size negates the use of variability measurement in the EMG signal. While measurement of average amplitude has been employed in previous studies (Wohlert & Hammen, 2000; Wohlert & Smith, 2002), it was not utilized in the present investigation because speech rate and intensity changes which are known to affect EMG signals were not directly controlled (Wohlert & Hammen, 2000).

### **Nature of Speech and Non-speech Tasks**

Past studies of AWS have shown that the degree of disfluency varies according to speech conditions. Chorus reading, lipped speech, prolonged speech, rhythmic speech,

shadowing, singing and slowed speech have been known to enhance fluency while increased stuttering has been linked to spontaneous speech (Andrews et al., 1983). In addition, cerebral activation is expected to differ according to cognitive demands placed by different speech conditions (Braun et al., 1997). The present study employed single-word production and single-sentence reading as speech tasks, and lip pursing as a non-speech task to evaluate hemisphere activation in AWS and AWNS. However, single-word productions, single-sentence reading and lip pursings may not accurately reflect the cognitive demands placed on AWS and AWNS for day-to-day speech processing. For example, past research suggests that the demands of propositional speech will generate greater left hemisphere activation as opposed to automatic speech in AWNS (Wolf & Goodale, 1987). Further, Braun et al. (1997) reported changes in cerebral activation as a result of increasing disfluency. Increased activity was observed in various regions of the left hemisphere as AWS participants became increasingly disfluent during spontaneous narrative speech and sentence construction tasks which more closely replicate daily speech conditions. Therefore, one might expect differences in hemispheric activation and accordingly, lip muscle activity between AWS and AWNS to increase as a function of cognitive demands and associated emotions related to speech processing. Accordingly, experimental tasks must be able to reflect various cognitive demands related speech production in AWS.

### **Other Methods of Evaluations**

As previously mentioned, lip asymmetry was apparent in studies based on acoustic, video and electronic tracking assessments (Code et al., 2005; Graves et al., 1982; Graves & Potter, 1998; Hausmann et al., 1998; Nicholls et al., 2004; Wolf & Goodale, 1987). In contrast, results based on EMG activity have been ambivalent (Wohlert & Goffman, 1994;

Wohlert & Hammen, 2000; Wohlert & Smith, 2002). In light of the equivocal outcomes generated by EMG procedure, other methods of evaluating cerebral lateralization in addition to EMG should be employed concurrently to provide a more comprehensive and accurate assessment. Further, each participant's emotion attached to speech and non-speech tasks was not formally evaluated in the present study. Although the AWS participants reported that they generally associated speech production with negative emotions, and the opposite were expressed by the AWNS participants, the assessment of emotion was not quantified. Instruments for describing the emotional state that are expressed in speech are available (Cowie & Cornelius, 2003). Cerebral activation related to both positive and negative emotions in the absence of speech production should be assessed and may provide a basis for comparison to emotion related to speech production.

### **Directions for Future Research**

Past brain imaging studies have highlighted differences between males and females in cerebral activation. AWNS males exhibit more left-lateralized activity than AWNS females who were more bilaterally activated during language processing (Bourne, 2005; Kent, 1998). This pattern has also been observed in AWS individuals with the difference of right-hemisphere lateralization for language processing in males (Ingham et al., 2004). Interestingly, investigations of lip asymmetry related to sex have been equivocal. Wolf and Goodale (1987) documented greater lip asymmetry in AWNS females than AWNS males. While Hausmann et al. (1998) and Graves et al. (1982) reported greater lip asymmetry in AWNS males. Differences in lip asymmetry associated with gender may be a consequence of disparities in the mode of linguistic and motor processing related to the nature of the tasks. The studies by Graves et al. and Hausmann et al. investigated lip asymmetry during continuous word production where participants were asked to describe a picture or generate words starting with certain phonemes. In contrast, Wolf and Goodale investigated lip asymmetry in single-movement word productions where the participants reproduced syllables or movements demonstrated by the experimenter. The discordant results may be ascribed to differences in language processing due to disparities in cerebral representation between males and females, and the nature of the tasks (Kent, 1998). Accordingly, observations of lip asymmetry (or the lack of it) in males cannot be generalized to females. The present study consisted of ten males, five of whom were AWS. Future research must include female participants to address gender differences in cerebral activation and lip movement.

Additionally, future research should evaluate AWS with- and without history of fluency treatment to evaluate the influence of treatment on cerebral activation patterns. Cerebral activation is anticipated to differ as a consequence of fluency enhancing

techniques. Neumann et al. (2003) reported increased left cerebral activation after therapy in AWS. Therefore, future investigations should include AWS with varying degrees of stuttering severity to evaluate differences in cerebral activation. Differences in orofacial movements (including the lower lips) associated with stuttering severity have been reported (McClean et al., 2004). AWS in the present study ranged from very mild to moderate stuttering. Several studies have reported greater activation in the right inferior frontal cerebral regions of AWS of moderate severity in comparison to AWS who were more affected (Neumann et al., 2003; Preibisch et al., 2003). Disparities related to stuttering severity are expected to manifest in cerebral activation and lip activity. Differences in treatment programs must be considered as they directly affect speech production (Tasko et al., 2007). Future investigations, should recruit participants that employ similar techniques for fluency if the efficacy of the programs are not under scrutiny.

Stuttering has been viewed as a multifactorial disorder related to both anatomy and function (Smith & Kelly, 1997). Past research has linked stuttering to other speech structures besides the lips including the larynx, jaw and tongue. Therefore, investigations focused only on lip muscles offer a limited view of the mechanisms and neural input involved in speech coordination and processing. Future investigations must include other speech structures. In addition, speech production is not a static phenomenon. Hence, future investigations should include kinematic measures that will offer a more complete and dynamic view of speech motor behavior and its related neural input.

EMG signals are affected by speech rate and intensity (Wohlert & Hammen, 2000). For future research, rate and intensity variables must be closely monitored. In addition, variations in orofacial activity and movement related to alterations in speech rate and intensity should be evaluated as they may help elucidate neural processes related to speech

processing (McClean & Tasko, 2003). Variations in habitual speech rate and loudness should also be considered. Measurements recorded during experimental tasks can be reported as a change from individual baseline or rest condition. Changes in speech clarity must also be examined as it is anticipated to involve motor control reorganization and may be similar to changes in speech intensity in terms of EMG activity (Wohlert & Hammen, 2000). Furthermore, resting potential must be considered in investigations of muscle asymmetry. Past investigations have highlighted asymmetry in muscle resting potential (Schmidt et al., 2006; Schwartz et al., 1979). The asymmetry of muscle resting potential may serve to confound measurements of asymmetry during experimental tasks and must be considered to accurately ascertain cerebral input.

Other speech and muscle parameters including durations of muscle activity and lip movement onset should be evaluated as they offer insight into speech planning and execution. Past studies have reported delayed movement of the lips, longer durations of lip muscle activity, slower speech onset and reversed sequence of lip movement in AWS when compared to AWNS even during fluent speech (De Nil, 1995; Logan, 2003; van Lieshout et al., 1996a, 1996b). Studies that include assessments of muscle duration and movement onset will offer better insight into speech planning and motor behavior. Consequently, EMG activity prior to-, during- and after-movement execution should be evaluated to accurately determine changes in EMG signal which is assumed to be a direct gauge of the variability in cerebral input during various phases of speech organization (Wohlert & Smith, 2002).

Linguistic demands and consequently, competition between cerebral hemispheres for neural resources have been cited as a component in stuttering (Bernstein-Ratner, 1997; Perkins et al., 1991; Starkweather & Gottwald, 1990). Bosshardt and Fransen (1996) found that AWS processed linguistic information at a slower rate than AWNS. Therefore, future



studies must encompass speech conditions that allow AWS to operate within the “normal” limits of fluency and those that are “stutter-inducing” to elucidate differences in neural processing and motor control. In addition, common practices in stuttering therapy such as pseudo-stuttering and prolonged speech should be investigated as they will offer insight into neural processing of AWS. One would expect a shift towards “normalized” pattern of lip activity in AWS as an indication of changes in cerebral activation as a consequence of reduced compensatory mechanism or changes in language use following fluency treatment.

Past studies employing other methods of evaluation such as video imaging and facial tracking have consistently reported lip asymmetry while those employing EMG have been erratic. Future investigations should include various forms of evaluations to eliminate the possibility of equipment or recording procedure as a confounding factor. In addition, video and acoustic measures obtained concurrently with muscle activity may provide a more comprehensive evaluation speech processing in AWS.

## Summary and Conclusion

Based on examination of peak EMG amplitude at four lip sites around the mouth, significant differences were found between speaker groups. There was a pattern whereby the highest and lowest EMG values at the lip locations were in direct opposition for the AWS and AWNS groups. The highest EMG amplitude for the AWS and AWNS groups were on the left and right sides of the mouth, respectively. The disparity in the location of highest EMG amplitude is suggestive of differences in cerebral activation during speech production, that is, AWS were right hemisphere dominant while the AWNS were left hemisphere lateralized. The most compelling evidence of differences between the groups was in regard to the correlations between EMG signals at various lip locations. The AWNS groups showed significant correlations between the four lip sites, suggestive of synchrony in EMG activity during the production of speech and non-speech tasks. In contrast, the AWS group only demonstrated a significant correlation between the upper and lower lip muscles on the left side of the face, indicating a lack of overall synchronous lip activity during speech and non-speech tasks. The pattern of lip activity demonstrated in the present study was taken as evidence of differences between AWS and AWNS in cerebral activation governing lip EMG activity at the moment of speech production and is consistent with previous investigations reporting reversed cerebral lateralization for speech and asymmetry of mouth opening in AWS.

The results of the present study also confirm EMG as a method for evaluating mouth asymmetry at the moment of speech production. In addition, the results were also consistent with the Right Hemisphere and Valence Hypotheses of emotional expressions reinforcing the need to quantify and examine the contribution of emotion to speech production in AWS.

## References

- Abbs, J.H., & Gracco, V.L. (1984). Control of complex motor gestures: Orofacial muscle responses to load perturbations of lip during speech. *Journal of Neurophysiology*, 51(4), 705-723.
- Alm, P.A. (2004). Stuttering and the basal ganglia circuits: A critical review of possible relations. *Journal of Fluency Disorders*, 37, 325-369.
- Alm, P.A., & Risberg, J. (2007). Stuttering in adults: The acoustic startle response, temperamental traits, and biological factors. *Journal of Communication Disorders*, 40, 1-41.
- Andrews, G., Hoddinott, S., Craig, A., Howie, P., & Feyer, A.M. (1983). Stuttering: A review of research findings and theories circa 1982. *Journal of Speech and Hearing Disorders*, 48(3), 226-246.
- Ambrose, N.G., & Yairi, E. (1999). Normative disfluency data for early childhood stuttering. *Journal of Speech Language and Hearing Research*, 42 (4), 895-909.
- Annett, M. (1972). The distribution of manual asymmetry. *British Journal of Psychology*, 63, 343-358.
- Arnold, H.S., Karrass, J., Conture, E.G., Walden, T.A., Williams, S.M., & Key, A.F. (2006). *Emotional reactivity and regulation in young children who stutter: Preliminary behavioral and brain activity data*. Retrieved on April 14, 2008 from American Speech-Language -Hearing Association: [http://convention.asha.org/2006/handouts/855\\_1336Arnold\\_Hayley\\_071711\\_111406083739.pdf](http://convention.asha.org/2006/handouts/855_1336Arnold_Hayley_071711_111406083739.pdf)
- Awh, E., & Gehring, W.J. (1999). The anterior cingulate cortex lends a hand in response selection. *Nature Neuroscience*, 2(10), 853-854.

- Batliner, A., Steidl, S., Hacker, C., & Nöth, E. (2008). Private emotions versus social interaction: a data-driven approach towards analyzing emotion in speech. *User Modeling and User-Adapted Interaction*, 18(1-2), 1573-1391.
- Beal, D.S., Gracco, V.L., Lafaille, S.J., & De Nil, L. (2007). Voxel-based morphometry of auditory and speech-related cortex in stutterers. *NeuroReport*, 18(1), 1257-1260.
- Beaton, A. (1985). *Left Side, Right side: A review of laterality research*. New Haven, CT: Yale University Press.
- Beeman, M.J., & Chiarello, C. (1998). Complementary right- and left-hemisphere language comprehension. *Current Directions in Psychological Science*, 7(1), 2-8.
- Bernstein-Ratner, N. (1997). Stuttering: A psycholinguistic perspective. In: R.F. Curlee, & G.M. Siegel (Eds.), *Nature and treatment of stuttering* (pp. 99-127). Needham Heights, MA: Allyn & Bacon.
- Biermann-Ruben, K., Salmelin, R., & Schnitzler, A. (2005). Right rolandic activation during speech perception in stutterers: a MEG study. *NeuroImage*, 25(3), 793-801.
- Binder, J.R., Frost, J.A., Hammeke, T.A., Rao, S.M., & Cox, R.W. (1996). Function of the left planum temporale in auditory and linguistic processing. *Brain*, 119, 1239-1247.
- Bishop, D.V.M. (1990). *Handedness and developmental disorder*. Exeter, UK: Lawrence Erlbaum Associates, Ltd.
- Blair, C., & Smith, A. (1986). EMG Recording in Human Lip Muscles: Can Single Muscles Be Isolated? *Journal of Speech and Hearing Research*, 29, 256 - 266.
- Blomgren, M., Nagarajan, S., Lee, J.N., Li, T., & Alvord, L. (2003). Preliminary results of a functional MRI study of brain activation patterns in stuttering and nonstuttering speakers during a lexical access task. *Journal of Fluency Disorders*, 28(4), 337-356.

- Blood, G.W., & Blood, I.M. (1989). Laterality preferences in adult female and male stutterers. *Journal of Fluency Disorders*, 14, 1-10.
- Bloodstein, O. (1987). *A handbook on stuttering* (4th ed.). Chicago: National Easter Seal Society.
- Bloodstein, O. (2006). Some empirical observations about early stuttering: A possible link to language development. *Journal of Communication Disorders*, 39, 185-191.
- Boberg, E., Yeudall, L.T., Schopflocher, D., & Bo-Lassen, P. (1983). The effect of an intensive behavior program on the distribution of EEG alpha power in stutterers during the processing of verbal and visuospatial information. *Journal of Fluency Disorders*, 8, 245-263.
- Borod, J.C., Kent, J., Koff, E., Martin, C., & Alpert, M. (1988). Facial asymmetry while posing positive and negative emotions: support for the right hemisphere hypothesis. *Neuropsychologia*, 26(5), 759-764.
- Bosshardt, H., & Fransen, H. (1996). Online Sentence Processing in Adults Who Stutter and Adults Who Do Not Stutter. *Journal of Speech and Hearing Research*, 39, 785-797.
- Bourne, V.J. (2005). Lateralised processing of positive facial emotion: sex differences in strength of hemispheric dominance. *Neuropsychologia*, 43, 953-956.
- Brady, J.P., & Berson, J. (1975). Stuttering, dichotic listening, and cerebral dominance. *Archives of General Psychiatry*, 32, 1449-1452.
- Braun, A.R., Varga, M., Stager, S., Schulz, G., Selbie, S., Maisog, J.M., Carson, R.E., & Ludlow, C.L. (1997). Altered patterns of cerebral activity during speech and language in developmental stuttering. An H<sub>2</sub><sup>15</sup>O positron emission tomography study. *Brain*, 120, 761-784.

- Brown, S., Ingham, R.J., Ingham, J.C. Laird, A.R., & Fox, P.T. (2005). Stuttered and fluent speech production: An ALE meta-analysis of functional neuroimaging studies. *Human Brain Mapping*, 25, 105-117.
- Buchél, C., & Sommer, M. (2004). What causes stuttering? *PLoS Biology*, 2(2): 159-163.
- Busso, C., & Narayanan, S.S. (2007). Interrelation between speech and facial gestures in emotional utterances: A single subject study. *IEEE Transactions on Audio, Speech and Language Processing*, 15(8), 2331-2347.
- Byrne R.A., Kuba M.J., Meisel, D.V., Griebel, U., & Mather, J.A. (2006). Does *Octopus vulgaris* have preferred arms? *Journal of Comparative Psychology*, 120(3), 198-204.
- Cacioppo, J.T., & Petty, R.E. (1979). Lip and nonpreferred forearm EMG activity as a function of orienting task. *Biological Psychology*, 9(2), 103-113.
- Cacioppo, J.T., & Petty, R.E. (1981). Electromyograms as a measure of extent and affectivity of information processing. *American Psychologist*, 36(5), 441-456.
- Cadalbert, A., Landis, T., Regard, M., & Graves, R. (1994). Singing with and without words: Hemispheric asymmetries in motor control. *Journal of Clinical and Experimental Neuropsychology*, 16(5), 664-670.
- Carlisle, J.A. (1985). *Tangled Tongue*. Reading, MA: Addison-Wesley Publishing Co.
- Chang, S., Erickson, K.I., Ambrose, N.G., Hasegawa-Johnson, M.A., & Ludlow, C.L. (2008). Brain anatomy differences in childhood stuttering. *NeuroImage*, 39, 1333-1344.
- Chiarello, C., Kacinik, N.A., Shears, C., Arambel, S.R., Halderman, L.K., & Robinson, C.S. (2006). Exploring cerebral asymmetry for the verb generation task. *Neuropsychology*, 20(1), 88-104.

- Code, C. (1979). Genuine and artificial stammering: An EMG comparison. *British Journal of Communication Disorders*, 14(2), 5-16.
- Code, C., Lincoln, M., & Dredge, R. (2005). Asymmetries in mouth opening during word generation in male stuttering and non-stuttering participants. *Laterality*, 10(5), 471-486.
- Compumedics. (2003). NeuroScan SynAmps<sup>2</sup>. [Computer Programme]. Charlotte, NC: Compumedics.
- Conture, E.G. (1990). *Stuttering* (2nd ed.). Englewoods Cliffs, NJ: Prentice-Hall.
- Conture, E., Colton, R., & Gleason, J. (1988). Selected temporal aspects of coordination during fluent speech of young stutterers. *Journal of Speech and Hearing Research*, 31, 640-653.
- Corballis, M.C. (2003). From mouth to hand: Gesture, speech, and the evolution of right-handedness. *Behavioral and Brain Sciences*, 26, 199-260.
- Cowie, R., & Cornelius, R.R. (2003). Describing the emotional states that are expressed in speech. *Speech Communication*, 40, 5-32.
- Craig, A., Hancock, K., Tran, Y., & Craig, M. (2003). Anxiety levels in people who stutter: A randomized population study. *Journal of Speech, Language, and Hearing Research*, 46, 1197-1206.
- Cram, J.R., Kasman, G.S., & Holtz, J. (1998). *Introduction to Surface Electromyography*. Gaithersburg, Maryland: Aspen Publishers, Inc.
- Cuadrado, E.M., & Weber-Fox, C.M. (2003). Atypical syntactic processing in individuals who stutter: Evidence from event-related brain potentials and behavioral measures. *Journal of Speech, Language, and Hearing Research*, 46, 960-976.

- Darley, F. L., Aronson, A. E. & Brown, J. R. (1975). *Motor Speech Disorders*. Philadelphia: Saunders.
- Davidson, R.J. (1992). Emotion and affective style: Hemispheric substrates. *Psychological Science*, 3, 39-43.
- Davidson, R.J., Jackson, D.C., & Kalin, N.H. (2000). Emotion, plasticity, context, and regulation: Perspectives from affective neuroscience. *Psychological Bulletin*, 126(6), 890-909.
- de Felicio, C. M., Rodrigues, R. L., Freitas, G., Vitti, M., & Regato, S.C.H.(2007). Comparison of upper and lower lip muscle activity between stutterers and fluent speakers. *International Journal of Pediatric Otorhinolaryngology*, 71(8), 1187-1192.
- De Nil, L. (1995). The influence of phonetic context on temporal sequencing of upper lip, lower lip, and jaw peak velocity and movement onset during bilabial consonants in stuttering and nonstuttering adults. *Journal of Fluency*, 20, 127-144.
- De Nil, L. (2004). Recent developments in brain imaging research in stuttering. In B. Massen, R.D. Kent, H.F.M. Peters, P. van Lieshout, & W. Hulstijn (Eds.), *Speech motor control in normal and disordered speech* (pp.113-138). New York: Oxford University Press.
- De Nil, L., & Kroll, R.M. (2001). Searching for the neural basis of stuttering treatment outcome: recent neuroimaging studies. *Clinical Linguistics & Phonetics*, 15(1-2), 163-168.
- De Nil, L., Kroll, R.M., & Houle, S. (2001). Functional neuroimaging of cerebellar activation during single word and verb generation in stuttering and non-stuttering adults. *Neuroscience Letters*, 302, 77-80.



- De Nil, L., Kroll, R.M., Lafaille, S.J., & Houle, S. (2003). A positron emission study of the short- and long-term effects on functional brain activation in adults who stutter. *Journal of Fluency Disorders*, 28, 357-380.
- De Nil, L., Kroll, R.M., Kapur, S., & Houle, S. (2000). A positron emission tomography study of silent and oral single word reading in stuttering and nonstuttering adults. *Journal of Speech, Language, and Hearing Research*, 43, 1038-1053.
- Diekhoff, G.M., Garlans, J., Dansereau, D.F., & Walker, C.A. (1978). Muscle tension, skin conductance, and finger pulse volume. *Acta Psychologica*, 42, 83-93.
- Dimberg, U., & Peterson, M. (2000). Facial reactions to happy and angry facial expressions: Evidence for right hemisphere dominance. *Psychophysiology*, 37, 693-696.
- Dorsaint-Pierre, R., Penhune, V.B., Watkins, K.E., Neelin, P., Lerch, J.P., Bouffard, M., & Zatorre, R.J. (2006). Asymmetries of the planum temporale and Heschl's gyrus: relationship to language lateralization. *Brain*, 129, 1164-1176.
- Egloff, B., Schmukle, S.C., Burns, L.R., & Schwerdtfeger, A. (2006). Spontaneous emotion regulation during evaluated speaking tasks: associations with negative affect, anxiety expression, memory, and physiological responding. *Emotion*, 6(3), 356-366.
- Elias, L.J., & Bryden, M.P. (1998). Footedness is a Better Predictor of Language Lateralisation than Handedness. *Laterality: Asymmetries of Body, Brain and Cognition*, 3(1), 41-52.
- Erk., S., Kleczar, A., & Walter, H. (2007). Valence-specific regulation effects in a working memory task with emotional context. *NeuroImage*, 37, 623-632.
- Ezrati-Vinacour, R., & Levin, I. (2004). The relationship between anxiety and stuttering: A multidimensional approach. *Journal of Fluency Disorders*, 29, 135-148.

- Fan, J., Hof, P.R., Guise, K.G., Fossella, J.A., & Postner, M.I. (2007). The functional integration of the anterior cingulate cortex during conflict processing. *Cerebral Cortex*, 18, 796-805.
- Fitzgerald, H.E., Cooke, P.A., & Greiner, J.R. (1984). Speech and bimanual hand organization in adult stutterers and nonstutterers. *Journal of Fluency Disorders*, 9, 51-65.
- Forster, D.C., & Webster, W.G. (1991). Concurrent task interference in stutterers: Dissociating hemispheric specialization and activation. *Canadian Journal of Psychology*, 45(3), 321-335.
- Foundas, A.L., Bollich, A.M., Corey, D.M., Hurley, M.M., & Heilman, K.M. (2001). Anomalous anatomy of speech-language areas in adults with persistent developmental stuttering. *Neurology*, 57, 207-215.
- Foundas, A.L., Corey, D.M., Angeles, V., Bollich, A.M., Crabtree-Hartman, E., & Heilman, K.M. (2003). Atypical cerebral laterality in adults with persistent developmental stuttering. *Neurology*, 61, 1378-1385.
- Foundas, A.L., Corey, D.M., Hurley, M.M., & Heilman, K.M. (2004). Verbal dichotic listening in developmental stuttering. *Cognitive and Behavioral Neurology*, 17(4), 224-232.
- Foundas, A.L., Leonard, C.M., Gilmore, R., Fennell, E., & Heilman, K.M. (1994). Planum temporale asymmetry and language dominance. *Neuropsychologia*, 32(10), 1225-1231.
- Fox, P.T., Ingham, R.J., Ingham, J.C., Hirsch, T.B., Hunter Downs, J., Martin, C., Jerabek, P., Glass, T., & Lancaster, J.L. (1996). A PET study of the neural systems of stuttering. *Nature*, 382, 158-162.

- Fox, P.T., Ingham, R.J., Ingham, J.C., Zamarripa, F., Xiong, J.H., & Lancaster, J.L. (2000). Brain correlates of stuttering and syllable production: A PET performance-correlation analysis. *Brain*, 123, 1985-2004.
- Freeman, F. J. (1979). Phonation in stuttering: A review of current research. *Journal of Fluency Disorders*, 4, 79-89.
- Freeman, F.J., & Ushijima, T. (1978). Laryngeal muscle activity during stuttering. *Journal of Speech and Hearing Research*, 21, 538-562.
- Fridlund, A.J. (1988). What can asymmetry and laterality in EMG tell us about the face and brain? *International Journal of Neurosciences*, 39 (1-2), 53-69.
- Frigio, C., Ferrarin, M., Frasson, W., Pavan, E., & Thorsen, R. (2000). EMG signals detection and processing for on-line control of functional electrical stimulation. *Journal of Electromyography and Kinesiology*, 10, 351-360.
- Gabriel, D.A, Kamen, G. & Frost, G. (2006). Neural adaptations to resistive exercise. *Sports Medicine*, 36(2), 133-149.
- Gautheron, B., Liorzou, A., Even, C., & Vallancien, B. (1973). The role of the larynx in stuttering. *Proceedings of the International Symposium on Stuttering* (pp. 43-46). The Hague: Mouton.
- Gerdle, B., Karlsson, S., Day, S., & Djupsjöbacka, M. (1999). Acquisition, processing and analysis of the surface electromyogram. In U. Windhorst, & H. Johansson (Eds.), *Modern Techniques in Neuroscience Research* (pp.705-753). Germany: Springer-Verlag.
- Goffman, L., & Smith, A. (1994). Motor unit territories in the human perioral musculature. *Journal of Speech and Hearing Research*, 37, 975-984.

- Giraud, A., Neumann, K., Bachoud-Levi, A., von Gudenberg, A.W., Euler, H.A., Lanfermann, H., & Preisbich, C. (2008). Severity of dysfluency correlates with basal ganglia activity in persistent developmental stuttering. *Brain and Language*, 104, 190-199.
- Gordon, N. (2002). Stuttering: incidence and causes. *Developmental Medicine and Child Neurology*, 44, 278-282.
- Gracco, V.L., & Abbs, J.H. (1985). Dynamic control of the perioral system during speech: Kinematic analyses of autogenic and nonautogenic sensorimotor processes. *Journal of Neurophysiology*, 54, 418-432.
- Graves, R., Goodglass, H., & Landis, T. (1982). Mouth asymmetry during spontaneous speech. *Neuropsychologia*, 20(4), 371-381.
- Graves, R., & Landis, T. (1990). Asymmetry in mouth opening during different speech tasks. *International Journal of Psychology*, 25, 179-189.
- Graves, R., & Potter, S. (1988). Speaking from two sides of the mouth. *Visible Language*, 22, 128-137.
- Greiner, J. R., Fitzgerald, H.E., & Cooke, P.A. (1986a). Bimanual hand writing in right-handed and left-handed stutterers and non-stutterers. *Neuropsychologia*, 24(3), 441-447.
- Greiner, J. R., Fitzgerald, H.E., & Cooke, P.A. (1986b). Speech fluency and hand performance on a sequential tapping task in left- and right-handed stutterers and nonstutterers. *Journal of Fluency Disorder*, 11, 55-69.
- Guitar, B. (1975). Reduction of stuttering frequency using analog electromyographic feedback. *Journal of Speech and Hearing Research*, 18, 672-685.

- Guitar, B. (1997). Therapy for children's stuttering and emotions. In: R.F. Curlee, & G.M. Siegel (Eds.), *Nature and treatment of stuttering* (pp. 280-291). Needham Heights, MA: Allyn & Bacon.
- Guitar, B. (2003). Acoustic Startle Responses and Temperament in Individuals Who Stutter. *Journal of Speech, Language, and Hearing Research*, 46, 233-240.
- Guitar, B. (2006). *Stuttering: An integrated approach to its nature and treatment* (3rd ed.). Philadelphia: Lippincott Williams & Wilkins.
- Guitar, B., Guitar, C., Neilson, P., O'Dwyer, N., & Andrews, G. (1988). Onset sequencing of selected lip muscles in stutterers and nonstutterers. *Journal of Speech and Hearing Research*, 31, 28-35.
- Güntürkün, O. (2003). Adult persistence of head-turning asymmetry. *Nature*, 421, 711.
- Haaland, K.Y., & Harrington, D.L. (1996). Hemispheric asymmetry of movement. *Current Opinion in Neurobiology*, 6, 796-800.
- Halliday, M.A.K. (2004). *An introduction to functional grammar* (3rd ed). London: Arnold Publishers.
- Hanna, R., Wilfling, F., & McNeill, B. (1975). A biofeedback treatment for stuttering. *Journal of Speech and Hearing Disorders*, 40, 270-273.
- Harris, L.J. (2000). Lateral biases for holding infants: Early opinions, observations, and explanations, with some possible lessons for theory and research today. *Brain and Cognition*, 48(2-3), 392-394.
- Hasbrouck, J.M., & Lowry, F. (1989). Elimination of stuttering and maintenance of fluency by means of airflow, tension reduction and discriminative stimulus control procedures. *Journal of Fluency Disorders*, 14, 165-183.

- Hausmann, M., Behrendt-Körbitz, S., Kautz, H., Lamm, C., Radelt, F., & Güntürkün, O. (1998). Sex differences in oral asymmetries during word repetition. *Neuropsychologia*, 36(12), 1397-1402.
- Hervé, P., Crivello, F., Perchey, G., Mazoyer, B., & Tzourio-Mazoyer, N. (2006). Handedness and cerebral anatomical asymmetries in young adult males. *NeuroImage*, 29, 1066-1079.
- Hoefl, F., Ueno, T., Reiss, A., Meyler, A., Whitfield-Gabrieli, S., Glover, G., Keller, T., Kobayashi, N., Mazaika, P., Jo, B., Just, M.A., & Gabrieli, J.D.E. (2007). Prediction of children's reading skills using behavioral, functional, and structural neuroimaging measures. *Behavioral Neuroscience*, 121(3), 602-613.
- Hoehn-Saric, R., Hazlett, R.L., Pourmotabbed, T., & McLeod, D.R. (1997). Does muscle tension reflect arousal? Relationship between electromyographic and electroencephalography recordings. *Psychiatry Research*, 71, 49-55.
- Hof, A.L. (1984). EMG and muscle force: An introduction. *Human Movement Science*, 3, 119-153.
- Holland, S.K., Plante, E., Byars, A.W., Strawsburg, R.H., Schmithorst, V.J., & Ball, W.S. (2001). Normal fMRI brain activation patterns in children performing a verb generation task. *NeuroImage*, 14, 837-843.
- Holland, S.K., Vannest, J., Mecoli, M., Jacola, L.M., Tillema, J., Karunanayaka, P.R., Schmithorst, V.J., Yuan, W., Plante, E., & Byars, A.W. (2007). Functional MRI of language lateralization during development in children. *International Journal of Audiology*, 46, 533-551.
- Holowka, S., & Petitto, L.A. (2002). Left hemisphere cerebral specialization for babbling while babbling. *Science*, 297, 1515.
- Howell, P. (2007). Signs of developmental stuttering up to age eight and at 12 plus. *Clinical Psychology Review*, 27, 287-306.

- Howell, P., Davis, S., & Williams, S.M. (2006). Auditory abilities of speakers who persisted, or recovered, from stuttering. *Journal of Fluency Disorders*, 31(4), 257-270.
- Hulstijn, W., Summers, J.J., van Lieshout, P.H.M., & Peters, H.F.M. (1992). Timing in finger tapping and speech: A comparison between stutterers and fluent speakers. *Human Movement Science*, 11, 113-124.
- Ingham, R.J., Fox, P., Ingham, J.C., & Zamarippa, F. (2000). Is overt stuttered speech a prerequisite for the neural activations associated with chronic developmental stuttering? *Brain and Language*, 75, 163-194.
- Ingham, R.J., Fox, P., Ingham, J.C., Xiong, J., Zamarripa, F., Hardies, L.J., & Lancaster, J.L. (2004). Brain correlates of stuttering and syllable production: Gender comparison and replication. *Journal of Speech, Language, and Hearing Research*, 47(2), 321-341.
- Ingham, R.J., Warner, A., Byrd, A., & Cotton, J. (2006). Speech effort measurement and stuttering: Investigation the chorus reading effect. *Journal of Speech, Language, and Hearing Research*, 49, 660-670.
- Jancke, L., Hanggi, J., & Steinmetz, H. (2004). *Morphological brain differences between adult stutterers and non-stutterers*. Retrieved on March 1, 2007 from BMC Neurology online:  
<http://www.biomedcentral.com/1471-2377/4/23>
- Janssen, P., Wieneke, G., & Vaane, E. (1983). Variability in the initiation of articulatory movements in the speech of stutterers and normal speakers. *Journal of Fluency Disorders*, 8, 341-358.
- Johannsen, H.S., & Victor, C. (1986). Visual information processing in the left and right hemispheres during unilateral tachistoscopic stimulation of stutterers. *Journal of Fluency Disorders*, 11, 285-291.

- Johnson, W. (1944). The Indians have no word for it. I. Stuttering in children. *Quarterly Journal of Speech*, 30, 330-337.
- Johnson, W., Boehmler, R.M., Dahlstrom, W.G., Darley, F.L., Kools, J., Neeley, J., Prather, W., Sherman, D., Thurman, C., Trotter, W., Williams, D., & Young, M. (1959). *The onset of stuttering*. Minneapolis: University of Minnesota Press.
- Kalotkin, M., Manschreck, T., & O'Brien, D. (1979). Electromyographic tension levels in stutterers and normal speakers. *Perceptual and Motor Skills*, 49(1), 109-110.
- Kasai, K., Shenton, M.E., Salisbury, D.F., Hirayasu, Y., Onitsuka, T., Spencer, M.H., Yurgelun-Todd, D.A., Kikinis, R., Jolesz, F.A., & Carley, R.W. (2003). Progressive decrease of left Heschl gyrus and planum temporale gray matter volume in first-episode schizophrenia. *Archives of General Psychiatry*, 60, 766-775.
- Kelly, E.M., Smith, A., & Goffman, L. (1995). Orofacial muscle activity of children who stutter: A preliminary study. *Journal of Speech and Hearing Research*, 38, 1025-1036.
- Kent, R.D. (1983). Facts about stuttering: Neuropsychologic perspectives. *Journal of Speech and Hearing Disorders*, 48, 249-255.
- Kent, R.D. (1998). Neuroimaging studies of brain activation for language, with an emphasis on functional magnetic resonance imaging: A review. *Folia Phoniatrica et Logopaedica*, 50, 291-304.
- Kent, R.D. (2004a). Models of speech motor control: Implications from recent developments in neurophysiological and neurobehavioral science. In B. Massen, R.D. Kent, H.F.M. Peters, P. van Lieshout, & W. Hulstijn (Eds.), *Speech motor control in normal and disordered speech* (pp.113-138). New York: Oxford University Press.



- Kent, R.D. (2004b). The uniqueness of speech among motor systems. *Clinical Linguistics & Phonetics*, 18(6-8), 495-505.
- Killgore, W.D.S, & Yurgelun-Todd, D. A. (2007). The right-hemisphere and valence hypotheses: Could they both be right (and sometimes left)? *Social Cognitive and Affective Neuroscience*, 2(3), 240-250.
- Knecht, S., Dräger, B., Deppe, M., Bobe, L., Lohmann, H., Flöel, A., Ringelstein, E.B. & Henningsen, H. (2000). Handedness and hemispheric language dominance in healthy humans. *Brain*, 123, 2512-2518.
- Lanyon, R.I., Barrington, C.C., & Newman, A.C. (1976). Modification of stuttering through EMG biofeedback-Preliminary study, *Behavior Therapy*, 7(1), 96-103.
- Lapatki, B.G., Stegeman, D.F., and Jonas, I.E. (2003). A surface EMG electrode for the simultaneous observation of multiple facial muscles. *Journal of Neuroscience Methods*, 123, 117-128.
- Lazarus, R.S. (1999). *Stress and emotion: A new synthesis*. Springer, New York.
- Logan, K.J. (2003). The effect of syntactic structure upon speech initiation times of stuttering and non-stuttering speakers. *Journal of Fluency Disorders*, 28, 17-35.
- Loucks, T.M.J., De Nil, L., & Sasisekaran, J. (2007). Jaw-phonatory coordination in chronic developmental stuttering. *Journal of Communication Disorders*, 40(3), 257-272.
- Ludlow, C.L., & Loucks, T. (2003). Stuttering: A dynamic motor control disorder. *Journal of Fluency Disorders*, 28, 273-295.
- Magnée, M.J.C.M., de Gelder, B., van Engeland, H., & Kemner, C. (2007). Facial electromyographic information from faces and voices in individuals with pervasive developmental disorder. *Journal of Child Psychology and Psychiatry*, 48(11), 1122-1130.

- Marieb, E.N. (1992). *Human Anatomy and Physiology* (2<sup>nd</sup> ed.). Redwood City, CA: The Benjamin/Cummings Publishing Company, Inc.
- Martini, F. H. (2006). *Fundamentals of Anatomy & Physiology* (7<sup>th</sup> ed.). San Francisco, CA: The Benjamin/Cummings Publishing Company, Inc.
- Maupas, E., Paysant, J., Daite, A.M., Martinet, N., & André, J.M. (2002). Functional symmetries of the lower limbs. A comparison between clinical assessment of laterality, isokinetic evaluation and electrogoniometric monitoring of knees during walking. *Gait and Posture*, 16, 304-312.
- McCartney, G., & Hepper, P. (1999). Development of lateralized behaviour in the human fetus from 12 to 27 weeks' gestation. *Developmental Medicine & Child Neurology*, 41, 83-86.
- McClean, M.D. (1996). Lip-muscle reflexes during speech movement preparation in stutterers. *Journal of Fluency Disorders*, 21, 49-60.
- McClean, M., Goldsmith, H., & Cerf, A. (1984). Lower-lip EMG and displacement during bilabial disfluencies in adult stutterers. *Journal of Speech and Hearing Research*, 27, 342-349.
- McClean, M.D., & Tasko, S.M. (2003). Association of orofacial muscle activity and movement during changes in speech rate and intensity. *Journal of Speech, Language, and Hearing Research*, 46, 1387-1400.
- McClean, M.D., & Tasko, S.M. (2004). Correlation of orofacial speeds with voice acoustic measures in the fluent speech of persons who stutter. *Experimental Brain Research*, 159, 310-318.
- McClean, M.D., Tasko, S., & Runyan, C.M. (2004). Orofacial Movements Associated With Fluent Speech in Persons Who Stutter. *Journal of Speech, Language, and Hearing Research*, 47, 294-303.

- McGuiness, D., & Bartell, T.E. (1982). Lateral Asymmetry: Hard or Simple-Minded? *Neuropsychologia*, 20(6), 629-629.
- Menzies, R., Onslow, M., & Packman, A. (1999). Anxiety and Stuttering: Exploring a complex relationship. *American Journal of Speech-Language Pathology*, 8, 3-10.
- Messenger, M., Onslow, M., Packman, A., & Menzies, R. (2004). Social anxiety in stuttering: measuring negative social expectancies. *Journal of Fluency Disorders*, 29(3), 201-212.
- Miller, S., & Watson, B.C. (1992). The relationship between communication attitude, anxiety and depression in stutterers and non-stutterers. *Journal of Speech and Hearing Research*, 35, 789-798.
- Moore, W.H. (1984). Hemispheric alpha asymmetries during an electromyographic biofeedback procedure for stuttering. *Journal of Fluency Disorders*, 17, 143-162.
- Moore, W.H., & Lang, M.K. (1977). Alpha asymmetry over the right and left hemispheres of stutterers and control subjects preceding massed oral readings: A preliminary investigation. *Perceptual and Motor Skills*, 44, 223-230.
- Mulligan, H.F., Anderson, T.J., Jones, R.D., Williams, M.J., & Donaldson, I.M. (2003). Tics and developmental stuttering. *Parkinsonism and Related Disorders*, 9, 281-289.
- Munhall, K.G. (2001). Functional imaging during speech production. *Acta Psychologica*, 107, 95-117.
- Murdoch, B.E. (2004). Subcortical brain mechanisms in speech motor control. In B. Massen, R.D. Kent, H.F.M. Peters, P. van Lieshout, & W. Hulstijn (Eds.), *Speech motor control in normal and disordered speech* (pp.139-172). New York: Oxford University Press.

- Neumann, K., Euler, H. A., von Gudenberg, A.W., Giraud, L., Lanfermann, H., Gall, V., & Preibisch, C. (2003). The nature and treatment of stuttering as revealed by fMRI: A within- and between-group comparison. *Journal of Fluency Disorders*, 28(4), 381-410.
- Neumann, K., Preibisch, C., Euler, H.A., von Gudenberg, A.W., Lanfermann, H., Volker, G., & Giraud, A. (2005). Cortical plasticity associated with stuttering. *Journal of Fluency Disorders*, 30, 23-39.
- Newton, K.R., Blood, G.W., & Blood, I.M. (1986). Simultaneous and staggered dichotic word and digit tests with stutterers and nonstutterers. *Journal of Fluency Disorders*, 11, 201-216.
- Nicholls, M.E.R., & Searle, D.A. (2006). Asymmetries for the visual expression and perception of speech. *Brain and Language*, 97, 322-331.
- Nicholls, M.E.R., Searle, D.A., & Bradshaw, J.L. (2004). Read my lips: Asymmetries in the visual expression and perception of speech revealed through the McGurk Effect. *Psychological Science*, 15(2), 138-141.
- Nolte, J. (2001). *The human brain: An introduction to its fundamental anatomy* (5<sup>th</sup> ed). Missouri: Mosby Inc.
- O'Beirne, G. (2008). MEP Analysator. University of Canterbury, New Zealand.
- O'Brian, S., Onslow, M., Cream, A., & Packman, A. (2003). The Camperdown Program: Outcomes of a new prolonged-speech treatment model. *Journal of Speech, Language and Hearing Research*, 46(4), 933-946.
- Oldfield, R.C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, 9(1), 97-113.

- Packman, A., Code, C., & Onslow, M. (2007). On the cause of stuttering: Integrating theory with brain and behavioral research. *Journal of Neurolinguistics*, 20, 353-362.
- Palolahti, M., Leino, S., Jokela, M., Kopra, K., & Paavilainen, P. (2005). Event-related potentials suggest early interaction between syntax and semantics during on-line sentence comprehension. *Neuroscience Letters*, 384, 222-227.
- Perkins, W.H., Kent, R.D., & Curlee, R.F. (1991). A Theory of Neuropsycholinguistic function in stuttering. *Journal of Speech and Hearing Research*, 34, 734-752.
- Platt, L.J., & Basili, A. (1973). Jaw tremor during stuttering block: An electromyographic study. *Journal of Communication Disorders*, 6, 102-109.
- Postma, A., & Kolk, H. (1993). The covert repair hypothesis: Prearticulatory repair processes in normal and stuttered disfluencies. *Journal of Speech and Hearing Research*, 36, 472-487.
- Preibisch, C., Neumann, K., Raab, P., Euler, H. A., von Gudenberg, A.W., Lanfermann, H., & Giraud, L. (2003). Evidence for compensation for stuttering by the right frontal operculum. *NeuroImage*, 20(2), 1356-1364.
- Prince, C.J., Winterburn, D., Giraud, A.L., Moore, C.J., & Noppeney, U. (2003). Cortical localization of the visual and auditory word form areas: A reconsideration of the evidence. *Brain and Language*, 86, 272-286.
- Prosek, R.A., Montgomery, A.A., Walden, B.E., & Schwartz, D.M. (1978). EMG biofeedback in the treatment of hyperfunctional voice disorders. *Journal of Speech and Hearing Disorders*, 43(3), 282-294.
- Raichle, M.E. (1996). What words are telling us about the brain. *Cold Spring Harbor Symposia on Quantitative Biology*, 61, 9-14.

- Rastatter, M.P., & Dell, C. (1987). Vocal reaction times of stuttering subjects to tachistoscopically presented concrete and abstract words: A closer look at cerebral dominance and language processing. *Journal of Speech and Hearing Research*, 30, 306-310.
- Rastatter, M.P., Loren, C., & Colcord, R. (1987). Visual coding strategies and hemispheric dominance characteristics of stutterers. *Journal of Fluency Disorders*, 12, 305-315.
- Rastatter, M.P., & Stuart, A. (1995). Hemispheric picture-naming hierarchies in stuttering subjects. *Perceptual and Motor Skills*, 81, 899-908.
- Riley, G. (1994). *Stuttering severity instrument for children and adults* (3rd ed.). Austin, Texas: Pro-Ed.
- Robinson, D. (1998). *Neurobiology: Biology, brain and behavior*. Berlin, New York: Springer in association with the Open University.
- Roeleveld, K., Sandberg, A., Stalberg, E.V., & Stegeman, D.F. (1998). Motor unit size estimation of enlarged motor units with surface electromyography. *Muscle & Nerve*, 21, 878-886.
- Rosenfield, D.B. (1980). Cerebral dominance and stuttering. *Journal of Fluency Disorders*, 5, 171-185.
- Ruggieri, V., & Sabatini, N. (1982). Cerebral dominance and muscle tone at rest. *Perceptual and Motor Skills*, 54, 1063-1066.
- Saارين, T., Laaksonen, H., Parviainen, T., & Salmelin, R. (2006). Motor cortex dynamics in visuomotor production of speech and non-speech mouth movements. *Cerebral Cortex*, 16, 212-222.
- Sadeghi, H., Allard, P., Prince, F., & Labelle, H. (2000). Symmetry and limb dominance in able-bodied gait: A review. *Gait and Posture*, 12, 34-45.

- Sainburg, R.L. (2005). Handedness: Differential specializations for control of trajectory and position. *Exercise and Sport Sciences Reviews*, 33 (4), 206-213.
- Salmelin, R., Schnitzler, A., Schmitz, F., & Freund, F. (2000). Single word reading in developmental stutterers and fluent speakers. *Brain*, 123, 1184-1202.
- Schmidt, K.L., Liu, Y., & Cohn, J.F. (2006). The role of structural *facial* asymmetry in asymmetry of peak facial expressions. *Laterality: Asymmetries of Body, Brain and Cognition*, 11(6), 540-561.
- Schwartz, G.E., Ahern, G.L., & Brown, S.L. (1979). Lateralized facial muscle response to positive and negative emotional stimuli. *Psychophysiology*, 16(6), 561-571.
- Shapiro, A.I. (1980). An electromyographic analysis of the fluent and dysfluent utterances of several types of stutterers. *Journal of Fluency Disorders*, 5(3), 203-231.
- Sirota, A.D., & Schwartz, G.E. (1982). Facial muscle patterning and lateralization during elation and depression imagery. *Journal of Abnormal Psychology*, 9(1), 25-34.
- Smith, A. (1989). Neural drive to muscles in stuttering. *Journal of Speech and Hearing Research*, 32, 252-264.
- Smith, A., & Kelly, E. (1997). Stuttering: A dynamic multifactorial model. In: R.F. Curlee, & G.M. Siegel (Eds.), *Nature and treatment of stuttering* (pp. 207-217). Needham Heights, MA: Allyn & Bacon.
- Sommer, M., Koch, M.A., Paulus, W., Weiller, C., & Buchel, C. (2002). Disconnection of speech-relevant brain areas in persistent developmental stuttering. *Lancet*, 360, 380-383.
- Spencer, E., Packman, A., Onslow, M., & Ferguson, A. (2005). A preliminary investigation of the impact of stuttering on language use. *Clinical Linguistics & Phonetics*, 19(3), 191-201.

- Stager, S.V., Jeffries, K.J., & Braun, A.R. (2003). Common features of fluency-evoking conditions studied in stuttering subjects and controls: an H<sub>2</sub><sup>15</sup>O PET study. *Journal of Fluency Disorders*, 28 (4), 319-336.
- Stancher, G., Clara, Regolin, L., & Vallortigara, G. (2006). Lateralized righting behavior in the tortoise (*Testudo hermanni*). *Behavioral Brain Research*, 173(2), 315-319.
- Starkweather, C.W. (1987). *Fluency and stuttering*. Englewood Cliffs, NJ: Prentice-Hall.
- Starkweather, C.W. (1995). A simple theory of stuttering. *Journal of Fluency Disorders*, 20, 91-116.
- Starkweather, C.W., & Givens-Ackerman, J. (1997). *Stuttering: The PRO-ED studies in communicative disorders*. Austin, Texas: PRO-ED Inc.
- Starkweather, C.W., & Gottwald, S.R. (1990). The demands and capacities model: II. Clinical applications. *Journal of Fluency Disorders*, 15(3), 143-157.
- Stegeman, D.F., Blok, J.H., Hermens, H.J., & Roeleveld, K. (2000). Surface EMG models: Properties and applications. *Journal of Electromyography and Kinesiology*, 10, 313-326.
- Strub, R.L., Black, F.W., & Naeser, M.A. (1987). Anomalous dominance in sibling stutterers: Evidence from CT scan asymmetries, dichotic listening, neuropsychological testing, and handedness. *Brain and Language*, 30, 338-350.
- Sun, T., & Walsh, C.A. (2006). Molecular approaches to brain asymmetry and handedness. *Nature Reviews Neuroscience*, 7(8), 655-662.
- Sussman, H.M. (1982). Contrastive patterns of intrahemispheric interference to verbal and spatial concurrent tasks in right-handed, left-handed and stuttering populations. *Neuropsychologia*, 20(6), 675-684.



- Szelag, E., Herman-Jeglinska, A., & GarwarskaKolek, D. (1997). Hemispheric asymmetries in stutterers: Disorder severity and neuroticism? *Acta Psychologica*, 95(3), 299-315.
- Tasko, S.M., McClean, M.D., Runyan, C.M. (2007). Speech motor correlates of treatment-related changes in stuttering severity and speech naturalness. *Journal of Communication Disorders*, 40, 42-65.
- Thompson, J.K. (1982). Neuroanatomy, hemisphericity and facial asymmetry. *Neuropsychologia*, 20(6), 699-701.
- Travis, L. E. (1934). Dissociation of homologous muscle function in stuttering. *Archives of Neurology and Psychiatry*, 31, 127-133.
- Travis, L.E. (1978). The cerebral dominance theory of stuttering: 1931-1978. *Journal of Speech and Hearing Disorders*, 43(3), 278-281.
- Turner, K.C., Frost, L., Lisenbardt, D., McIlroy, J.R., & Müller, R. (2006). *Atypically diffuse functional connectivity between caudate nuclei and cerebral cortex in autism*. Retrieved on April 14, 2008 from *Behavioral and Brain Function* online: <http://www.behavioralandbrainfunctions.com/content/2/1/34>
- Van Agtmael, T., Forrest, S.M., Del-Favero, J., Van Broeckhoven. C., & Williamson, R. (2003). Parametric and nonparametric genome scan analyses for human handedness. *European Journal of Human Genetics*, 11, 779-783.
- Van Borsel, J., Achten, E., Santens, P., Lahorte, P., & Voet, T. (2003). *fMRI* of developmental stuttering: A pilot study. *Brain and Language*, 85(3), 369-376.
- van Lieshout, P.H.H.M., Peters, H.F.M., Starkweather, C.W., & Hulstijn, W. (1993). Physiological differences between stutterers and nonstutterers in perceptually fluent speech: EMG amplitude and duration. *Journal of Speech and Hearing Research*, 36, 55-63.

- van Lieshout, P.H.H.M., Hulstijn, W., & Peters, H.F.M. (1996a). From planning to articulation in speech production: What differentiates a person who stutters from a person who does not stutter? *Journal of Speech and Hearing Research*, 39, 546-564.
- van Lieshout, P.H.H.M., Hulstijn, W., & Peters, H.F.M. (1996b). Speech production in people who stutter: Testing the motor plan assembly hypothesis. *Journal of Speech and Hearing Research*, 39, 76-92.
- Van Riper, C. (1982). *The nature of stuttering* (2nd ed.) Englewood Cliffs, NJ: Prentice-Hall.
- Vaughn, C.D., & Webster, W.G. (1989). Bimanual handedness in adults who stutter. *Perceptual and Motor Skills*, 68, 375-382.
- Walla, P., Meyer, D., Deecke, L., & Thurner, S. (2004). The lack of focused anticipation of verbal information in stutterers: a magnetoencephalographic study. *NeuroImage*, 22: 1321-1327.
- Watkins, J., Miklosi, A., & Andrew, R.J. (2004). Early asymmetries in the behaviour of zebrafish larvae. *Behavioral Brain Research*, 151(1-2), 177-183.
- Watkins, K.E., Smith, S.M., & Davis, S., & Howell, P. (2008). Structural and functional abnormalities of the motor system in developmental stuttering. *Brain*, 131, 50-59.
- Watson, B.C., Freeman, F., Devous, M.D., Chapman, S.B., Finitzo, T., & Pool, K.D. (1994). Linguistic performance and regional cerebral blood flow in persons who stutter. *Journal of Speech and Hearing Research*, 37, 1221-1228.
- Weber-Fox, C. (2001). Neural systems for sentence processing in stuttering. *Journal of Speech, Language, and Hearing Research*, 44, 814-825.
- Webster, W.G. (1988). Neural mechanisms underlying stuttering: Evidence from bimanual handwriting performance. *Brain and Language*, 33, 226-244.

- Webster, W.G. (1990). Motor performance of stutterers: A search for mechanisms. *Journal of Motor Behavior*, 22(4), 553-571.
- Wells, B.G., & Moore, W.H. (1990). EEG alpha asymmetries in stutterers and non-stutterers: Effects of linguistic variables on hemispheric processing and fluency. *Neuropsychologia*, 28(12), 1295-1305.
- Wichmann, A. (2000). The attitudinal effects of prosody, and how they relate to emotion. In *Proceedings of ISCA / ITRW on Speech and Emotion: Developing a Conceptual Framework* (pp. 143-147). Newcastle, N.Ireland: Elsevier Science Publishers B.V.
- Wildgruber, D., Ackermann, H., Klose, U., Kardatzki, B., & Grodd, W. (1996). Functional lateralization of speech production at primary motor cortex: A fMRI study. *NeuroReport*, 7, 2791-2795.
- Wingate, M.E. (1988). *The structure of stuttering: A psycholinguistic analysis*. New York: Springer-Verlag.
- Wohlert, A.B. (1993). Event-related brain potentials preceding speech and non-speech oral movements of varying complexity. *Journal of Speech & Hearing Research*, 36(5), 897-905.
- Wohlert, A.B., & Goffman, L. (1994). Human perioral muscle activation patterns. *Journal of Speech and Hearing Research*, 37(5), 1032-1040.
- Wohlert, A.B., & Hammen, V.L. (2000). Lip muscle activity related to speech rate and loudness. *Journal of Speech, Language, and Hearing Research*, 43(5), 1229-1239.
- Wohlert, A.B., & Larson, C.R. (1991). Cerebral averaged potentials preceding oral movement. *Journal of Speech and Hearing Research*, 34, 1387-1396.
- Wohlert, A.B., & Smith, A. (2002). Developmental change in variability of lip muscle activity during speech. *Journal of Speech, Language, and Hearing Research*, 45(6), 1077-1087.

- Wolf, M. E., & Goodale, M.A. (1987). Oral asymmetries during verbal and non-verbal movements of the mouth. *Neuropsychologia*, 25(2), 375-396.
- Wyke, B. (1969). Deus ex machine vocis: An analysis of the laryngeal reflex mechanisms of speech. *British Journal of Disorders of Communication*, 4, 3-25.
- Yairi, E., & Ambrose, N. (2004). Stuttering: recent developments and future directions. *The ASHA Leader*, 4-5, 14-15.
- Yairi, E., Ambrose, N., & Cox, N. (1996). Genetics of stuttering: A critical review. *Journal of Speech and Hearing Research*, 39, 771-784.
- Zelaznik, H.N., Smith, A., Franz, E.A., & Ho, M. (1997). Differences in bimanual coordination associated with stuttering. *Acta Psychologica*, 96, 229-243.
- Zhou, R., & Hu, S. (2006). Study of posed emotion in facial EMG asymmetry. *Perceptual and Motor Skills*, 102, 430-434.
- Zwarts, M.J., Drost, G., & Stegeman, D.F. (2000). Recent progress in the diagnostic use of surface EMG for neurological diseases. *Journal of Electromyography and Kinesiology*, 10, 287-291.

## **Appendix I**

Edinburgh Handedness Inventory Questionnaire (Oldfield, 1971).

Note: Questions # a. and b were adapted from the Elias and Bryden (1998).

The Edinburgh Handedness Inventory Questionnaire

Date:

Time:

Participant:

Age:

Please check the box that applies to you.

Which hand do you prefer?

		LEFT	RIGHT	EITHER
1	Writing			
2	Drawing			
3	Throwing			
4	Scissors			
5	Toothbrush			
6	Knife (without a fork)			
7	Spoon			
8	Rake (upper hand)			
9	Striking a match or lighter			
10	Opening a box (lid)			

Do you ever use the other hand?

YES	NO

a	Which foot do you prefer to kick with?			
b	Which eye do you use when using only one?			

**Appendix II**  
Background Questionnaire

## Background Information

1. Do you have any known neurological disease? If yes, elaborate
2. Are you currently on any medication? If yes please describe.
3. Have you ever stuttered? Yes or No  
If the answer is "Yes", please describe the age of onset and your current speech.
4. Have you ever received therapy for stuttering? Please describe the therapy.
5. Do you have family members (immediate or otherwise) that stutter? If you do, how are they related to you and what is their speech like?



**Appendix III**

University of Canterbury Human Ethics Approval and Consent Forms

## Department of Communication Disorders



### Project Information

You are invited to participate in the research project, *“Hemispheric activation as indicated by lip activity in individuals who stutter”*.

The goal of this study is to examine brain activity that occurs in people who stutter compared to people who do not stutter.

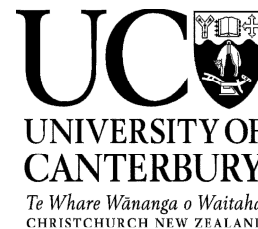
As a participant, you will be asked to name a total of 80 pictures and to purse your lips a total of 20 times. To record the lip activity, electrodes will be placed in 8 different locations around your lips. You will be asked to clean around your lip area with an alcohol wipe. This will remove any skin or hair oils which can interfere with electrode to skin contact. It will take approximately one hour to complete these tasks. You may choose to discontinue your participation in the project at anytime throughout the data collection period.

The results of the project may be published, however you may be assured of the complete confidentiality of data gathered in this investigation; the identity of participants will not be made public without their consent. To ensure anonymity and confidentiality, the information gathered will be assigned a number and all identifiable information removed. Data will be kept in a locked filing cabinet within a lockable room in the Department of Communication Disorders and will be destroyed on completion of the research. The researcher and her supervisor will be the only authorized persons to have access to the data.

The project is being carried out as a requirement for a M.Sc. in Psychology by Ai Leen Choo, (e-mail: [alc78@student.canterbury.ac.nz](mailto:alc78@student.canterbury.ac.nz)) under the supervision of Professor Michael Robb, who can be contacted at the University of Canterbury on 364-2987 (ext. 4813). They will be pleased to discuss any concerns you may have about participation in the project.

The project has been reviewed **and approved** by the University of Canterbury Human Ethics Committee.

## Department of Communication Disorders



Ai Leen Choo  
 Department of Psychology/ Communication Disorders  
 University of Canterbury  
 Creyke Road  
 Ilam  
 October 1, 2007

### Consent Form

*"Hemispheric activation as indicated by lip activity in individuals who stutter"*

I have read and understood the description of the above-named project. On this basis, I agree to my participation in the project, and I consent to publication of the results of the project with the understanding that anonymity will be preserved.

I understand that I may withdraw from the project at any time, including withdrawal of any information I have provided.

PARTICIPANT'S NAME (please print):

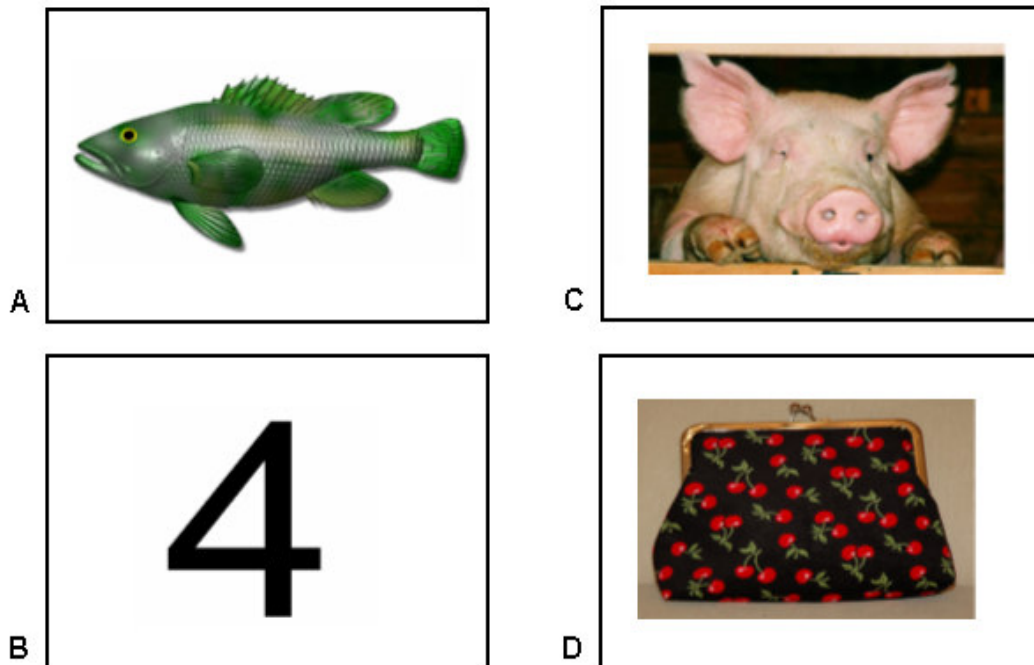
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Signature:

Date:

**Appendix IV**

Sample of the pictures presented to the participants.



Panels A and B are pictures of words beginning with /f/: *fish* and *four*. Panels C and D are picture of words starting with /p/: *pig* and *purse*.